REPORT 24

SWEEP

SOIL AND WATER

ENVIRONMENTAL

ENHANCEMENT PROGRAM

PAMPA

PROGRAMME D'AMÉLIORATION

DU MILIEU PÉDOLOGIQUE

ET AQUATIQUE

Canada

Ontario

SWEEP

is a $30 million federal-provincial agreement, announced May 8, 1986, designed to improve soil and water quality in southwestern Ontario over the next five years.

PURPOSES

There are two interrelated purposes to the program; first, to reduce phosphorus loadings in the Lake Erie basin from cropland run-off; and second, to improve the productivity of southwestern Ontario agriculture by reducing or arresting soil erosion that contributes to water pollution.

BACKGROUND

The Canada-U.S. Great Lakes Water Quality Agreement called for phosphorus reductions in the Lake Erie basin of 2000 tonnes per year. SWEEP is part of the Canadian agreement, calling for reductions of 300 tonnes per year — 200 from croplands and 100 from industrial and municipal sources.

PAMPA

est une entente fédérale-provinciale de 30 millions de dollars, annoncée le 8 mai 1986, et destinée à améliorer la qualité du sol et de l'eau dans le Sud-ouest de l'Ontario.

SES BUTS

Les deux buts de PAMPA sont: en premier lieu de réduire de 200 tonnes par an d'ici 1990 le déversement dans le lac Erie de phosphore provenant des terres agricoles, et de maintenir ou d'accroître la productivité agricole du Sud-ouest de l'Ontario, en réduisant ou en empêchant l'érosion et la dégradation du sol.

SES GRANDES LIGNES

L'entente entre le Canada et les États-unis sur la qualité de l'eau des Grands Lacs prévoyait de réduire de 2 000 tonnes par an la pollution due au phosphore dans le bassin du lac Erie. PAMPA fait partie de cette entente qui réduira cette pollution de 300 tonnes par an — 200 tonnes provenant des terres agricoles et 100 tonnes provenant de sources industrielles et municipales.

100-05256/

TECHNOLOGY EVALUATION AND DEVELOPMENT SUB-PROGRAM

INVESTIGATION OF SOIL AND CROP RESPONSE TO FALL SUBSOILING IN SOUTHWESTERN ONTARIO

FINAL REPORT

August, 1991

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TABLE OF CONTENTS

		Page
	Study Team	vi
	Acknowledgements	vi
	Executive Summary	vii
1.0	INTRODUCTION	1
1.1	Objectives	1
1.2	Literature Review	3
2.0	MATERIALS AND METHODS	6
2.1	Experimental Design	6
2.2	Subsoiling Implements	6
2.3	Climatic Records	6
2.4	Field Investigations	11
2.5	Statistical Analyses	16
2.6	Farmer Interviews	17
3.0	RESULTS	18
3.1	Climatic Conditions	18
3.2	Field Observations During The Growing Season	18
3.3	Soil Compaction Observations	19
3.4	1989 Effects of Subsoiling Treatments on Soil Properties	21
3.5	1989 Relationships Among Soil Properties and Management Factors	22
3.6	1990 Effects of Subsoiling Treatments on Soil Properties	25
3.7	Effects of Subsoiling Treatments on Yields	29
3.8	Yield Versus Management Practices and Soil Characteristics	34
3.9	1990 Pearson Correlation Analyses	34
3.10	Conditions Affecting Implement Draught	40
3.11	1989 Tractor Performance With Different Subsoilers	44
4.0	SUMMARY	48
5.0	RECOMMENDATIONS	51
6.0	REFERENCES	52
7.0	APPENDICES	54
7.1	Appendix A 1989 Input Data	54
7.2	Appendix B 1990 Input Data	72
7.3	Appendix C Variables used in Pearson Correlation Analyses - Codes and Explanations.	86
7.4	Appendix D Layout of Treatments at Each of the Field Sites	89

LIST OF TABLES

		Page
1.	List of Co-operators (Site No.), Implements Used, and Level of Detail of Data Collection	7
2.	Simple System for Describing Soil Macrostructure (from McKeague, et al., 1986)	12
3.	Soil Compaction Indicators: Subjective Rating (from Can-Ag Enterprises, 1988)	13
4.	Kent County Climatic Data	19
5.	1989 Soil Compaction Measurements	20
6.	1989 Pearson Correlation Matrix.	23
7.	1990 Soil Compaction Measurements (Comparison Between Soil Depths)	26
8.	1990 Soil Compaction Measurements (Comparison Between Subsoiling Treatments)	28
9.	Comparison of Pocket Penetrometer Resistance Readings (kg/cm^2) at Each Soil Layer Between the Years 1989 and 1990 for Each Subsoiling Treatment for Each Field	30
10.	Comparison of Bulk Density Readings (g/cm^3) in the AB and B Soil Layers for Each Subsoiling Treatment for Six Fields Between the Years 1989 and 1990	32
11.	1990 Mean Crop Yields, Type of Tillage, Fertilization, Previous Crop (1989), and Soil Characteristics (Texture, Topsoil Depth, and Organic Matter) for Each Site.	35
12.	1990 Pearson Correlation Matrix (Soil Fertility and Yields).	36
13.	1990 Pearson Correlation Matrix (Soil Physical Properties, Loading and Yields).	38
14.	1989 Implement Draught Calculations and Related Soil Parameters for Sites 7, 11, 12 and 14.	43
15.	Guidelines for Quantifying Compaction Indicators for Soils Examined.	55
16.	1989 Penetrometer Readings.	56
17.	1989 Bulk Densities.	60

LIST OF TABLES

Page

18. 1989 Worm, Pore, Compaction and Subsoiler Ratings. 63
19. 1989 Soil Fertility Results. 66
20. 1989 Particle Size Analysis. 67
21. 1989 Past Yield and Management Factors. 68
22. 1989 Management Factors: Fertilizer Additions (kg/ha). 69
23. 1989 Soil Moisture (%) at Time of Subsoiling. 70
24. 1990 Penetrometer Readings. 73
25. 1990 Bulk Densities. 77
26. 1990 Worm, Pore, Compaction and Subsoiler Ratings. 80
27. 1990 Soil Fertility Results. 83
28. 1990 Past Yield and Management Factors. 84
29. 1990 Management Factors: Fertilizer Additions (kg/ha). 85

LIST OF FIGURES

		Page
1.	Location of Co-operators' Sites	2
2.	Tye Paratill®	8
3.	Strohm aerator®	8
4.	B.C. Sub-mulcher®	9
5.	Agriculture Canada's computerized Research Tractor pulling the Paratill®	10
6.	Observation pit - Visual Assessment	10
7.	Investigation pit - Second and Third Level of Detail	14
8.	Pocket Penetrometer Measurement Procedure	14
9.	Dickey-john® Penetrometer	15
10.	Bulk Density Coring Procedure.	15
11.	1990 Soybean and Corn Yields One Year after Subsoiling with Different Implements.(For soybeans - Strohm aerator® and B.C Sub-mulcher®, n=6; Control n=8;Paratill® n=4: for corn - all subsoiling treatments n=12, except Paratill® n=6)	33
12.	Compaction (CR) versus Soil Pore (P) Ratings for Control Treatments in the AB Layer for Fourteen Sites in 1990.	39
13.	Comparison of Mean Dickey-john® Penetrometer Readings for 1989 and 1990 for Each Site.	41
14.	Comparison of Mean Pocket Penetrometer Readings for 1989 and 1990 for Each Site.	41
15.	Comparison of Mean Bulk Density Readings for 1989 and 1990 for Each Site.	42
16.	Comparison of Mean Compaction Ratings for 1989 and 1990 for Each Site.	42
17.	Draught in Newtons (N) needed to pull three subsoiling implements in several fields (M. Parry, Skipper, and Wonnacott)	45
18.	Fuel consumption (L/ha) used in pulling three subsoiling implements in several fields (M. Parry, Skipper, and Wonnacott)	45

LIST OF FIGURES

		Page
19.	Site 11 - Draught in Newtons (N) versus Fuel Use (L/ha) in 1989	47
20.	Site 1 (Bee) Layout of Treatments.	90
21.	Site 2 (Bradley Field #1) Layout of Treatments.	91
22.	Site 3 (Bradley Field #2) Layout of Treatments.	92
23.	Site 4 (Cumming) Layout of Treatments.	93
24.	Site 5 (Farquharson) Layout of Treatments.	94
25.	Site 6 (Hoy) Layout of Treatments.	95
26.	Site 7 (Johnstone) Layout of Treatments.	96
27.	Site 8 (Jack) Layout of Treatments.	97
28.	Site 9 (D. Parry) Layout of Treatments.	98
29.	Site 10 (G. Parry) Layout of Treatments.	99
30.	Site 11 (M. Parry) Layout of Treatments.	100
31.	Site 12 (Skipper) Layout of Treatments.	101
32.	Site 13 (Vince) Layout of Treatments.	102
33.	Site 14 (Wonnacott) Layout of Treatments.	103

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EXECUTIVE SUMMARY

Subsoil compaction is considered to be a serious problem in southwestern Ontario. Based on inspections of seventy fields chosen at random, approximately 15% and 45% of the clay to clay loam soils in five Counties in the southwest were found to be severely and moderately affected, respectively (Can-Ag Enterprises Ltd., 1988). The same study found corresponding crop yield declines to be some 25% and 12.5%, based on farmers reported yields for the fields inspected.

In 1988 a group of farmers initiated subsoiling experiments to examine corn response to interrow subsoiling in mid June. Can-Ag Enterprises Ltd. was contracted to monitor soil conditions and crop response. It was a very dry year and significant crop yield increases occurred on only two of the thirteen fields. These two fields had severely compacted soils: others were rated moderately compacted. A lack of response on moderately compacted soils was attributed to increased droughtiness following subsoiling and below average rainfall.

The current study commenced in the fall 1989, involving fourteen different fields but not all of the same farmers. Its objective was to determine the impact of subsoiling to a depth of about 30 cm after wheat harvest on subsequent crop yields. Three subsoiling implements were used in the research: Tye Paratill®; Strohm aerator®, and B.C. Sub-mulcher®. Field length strips (0.5 - 1 km long and 10 or 20 metres in width), two replicates each, were established to monitor effectiveness of each implement and a control.

Soils in each strip were examined to determine the degree and characteristics of compaction shortly after subsoiling in 1989 and again after the 1990 harvest. Measurements included hand and cone penetrometer readings, soil bulk densities on control plots, and detailed visual inspections of structure and pores. At a few fields, bulk densities were determined on all treatments.

The 1990 crop yields were measured by the farmers. They harvested each strip separately and used weigh wagons to determine yields. Farmers also shared their experience with respect to workability of the soils, ponding following rains, and their evaluation of the degree of compaction. In addition, they monitored all inputs including field operations, type of equipment used, fertilizer and herbicide inputs, and general crop performance during the growing season.

Statistical analyses were conducted to determine significant differences in crop response and soil conditions to the treatments. Also a Pearson correlation matrix was used to

identify significant correlations among various soil parameters, management inputs, and crop yields.

Results indicated significant changes in soil conditions to the different subsoilers, however, only two fields produced a substantial crop yield increase. Considering all plots as a group, there was not a significant yield response in 1990 to the fall 1989 subsoiling. Moisture conditions throughout the 1990 growing season were good, seldom being too wet or too dry.

Soil compaction was rated moderate on eleven fields, slight to moderate on one, and moderate to severe on two. Twelve of the fields were clayey, specifically, clay loams, silty clays and silty clay loams. The other two were sandy loams.

The Paratill® was the most effective implement in reducing soil compaction and soil differences remained visible and measurable in the fall 1990. The Strohm aerator® appeared to be slightly, but not significantly, more effective than the B.C. Sub-mulcher®.

Measurements of fuel consumption per hectare indicated highest requirements for the Strohm aerator® followed by the Paratill®, and then the B.C. Sub-mulcher®. The Paratill® required the highest draught followed by the Strohm aerator® and the B.C. Sub-mulcher®. This apparent anomaly is possibly due to malfunctioning draught pins in the computerized tractor providing questionable numbers. The lack of any wings on the shanks of the B.C. Sub-mulcher® makes it easiest to pull even though it had more shanks and was wider than the other subsoilers.

Examination of management inputs complicates interpretation of the results. Four farmers fall plowed their fields in 1989 (after subsoiling) as deep as they were subsoiled. This was their normal practice, perhaps a substitute for subsoiling. One of these fields was moderate to severely compacted, while the others were moderately compacted, all being clayey soils. A lack of yield response on these fields may therefore be due to deep plowing eliminating the effects of subsoiling. Of the two fields where good yield responses in soybeans were measured on the Paratill® treatments, on moderately compacted clayey soils, one was no-till the other was conservation tillage. Correlation analyses indicated a positive relationship between yields and soil fertility levels.

A lack of more noticeable yield responses in 1990 may be due to the relatively favourable moisture conditions through the growing season, even though soil conditions appeared to benefit from subsoiling. Furthermore, the fact that most of the sites were moderately compacted made it difficult to relate responses of yield to degree of compaction.

In the literature, mixed responses to subsoiling were reported. Our studies indicated

that compacted subsoils were widespread, however, crop responses to subsoiling have not been clearly predictable nor measurable. First, longer term studies are essential to encompass weather variability. To save costs, farmers should confine subsoiling to severely compacted sites until more is known about crop responses to subsoiling. Of the implements used, the Paratill® is considered to be the most effective subsoiler, keeping in mind that this is based on one year of data from four fields. In the heavy clay soils, tillage practices such as deep plowing or chiselling are also considered effective in ameliorating compaction at the 15 to 30 cm depth. Farmers should also be aware of other management practices which tend to alleviate soil compaction. These include:

- reduction in vehicle weights (axle loads),
- avoiding working on wet or very moist soils,
- limiting the number of passes over the field, especially if moist, and
- utilizing cropping systems and rotations which facilitate the above and provide crops with deep rooting action as well as maintain or improve soil organic matter content.

On severely compacted soils subsoiling may be viable, however, farmers should establish trials first to determine whether there is a significant and economical yield response. Adoption of the above mentioned practices is also advised to reduce re-compaction of the soils likely to occur in one or two years.

1.0 INTRODUCTION

Subsoil compaction at a depth of about 15 to 30 cm is a serious problem in agriculture. Cropping systems involving few annual crops, excessive tillage, heavy machinery, and operating on very moist soils (especially clayey soils), all contribute to soil compaction.

This report presents the results of a two year study on soil compaction, subsoiling with different implements, and crop responses. Fourteen sites throughout Kent County in southwestern Ontario were studied reflecting different soil types and tillage practices (Figure 1). Studies were conducted on replicated field scale strips. Participating farmers were eager to learn more about the effectiveness of subsoiling and their excellent co-operation is sincerely appreciated.

1.1 OBJECTIVES

In the fall of 1989, all the sites were subsoiled, and this was followed by thorough soil investigations. In the 1990 growing season the crops were monitored, harvested, and yields were obtained. Following the 1990 harvest, there was another fall investigation of soil characteristics.

The purpose of this study was to determine any beneficial soil changes induced by the subsoilers, that increased crop yields, and that improved soil quality, or reduced water and sediment runoff. The main objectives of this research were:

1. to determine the baseline soil characteristics in fields not previously subsoiled,
2. to compare the three subsoiling implements and evaluate their ameliorative abilities in terms of soil conditions, yield response, implications to erosion and phosphorous runoff, and economic benefits,
3. to determine the effectiveness of fall subsoiling in generating positive soil and crop responses, and
4. to monitor other related inputs and returns:
   - agronomic practices (tillage, fertilization, cropping, etc.);
   - rainfall (local rain gauge, nearby weather station);
   - crop yields; and
   - economic benefits.

Figure 1. Location of Co-operators' Sites.

1.2 LITERATURE REVIEW

A previous report by Can-Ag (1988), found that 50 to 70 percent of the clayey soils in the Counties of Middlesex, Lambton, Essex, Kent and Elgin are compacted to some degree. Farmers perform conventional tillage to reduce surface compaction, but have relied on natural alleviation for the reduction of subsurface compaction. Yet Gameda et al. (1987), studying clay soils at MacDonald College in Quebec, found bulk density reductions by wetting/drying and freezing/thawing and improvements in crop yields following a single application of high axle loading took substantially longer than three years. Therefore, the impacts of compaction may persist for a number of years (Voorhees et al. 1989). One key impact is the reduced infiltration leading to increased soil erosion as well as increased phosphorous runoff. Onwualu and Anazodo (1989), showed that soil moisture content and the presence of pores, significantly decreased as soil compaction increased. Soil strength as measured by bulk density and soil resistance to penetrometer pressure, significantly increased as soil compaction increased. The decreased soil porosity is due to reduction in the size of pores in the soil profile, thus leading to the reduced water infiltration. The altering of the soil physical properties not only limits aeration and water infiltration, but serves as an impedance to root growth. Questions arise though to how much these alterations can affect yields.

Studies from both the corn belt region of the mid-western United Stated, as well as Canada, have shown that soil compaction with heavy loads can have a detrimental effect on crop yields. Gaultney et al. (1982), observed over 50% yield reduction of corn grown on severely compacted subsoils in Indiana and an approximately 25% yield reduction on moderately - compacted plots. Gameda et al. (1983) found yield reductions as high as 40% due to axle loadings in the 9.1 to 18.1 ton range on clay soil in Quebec. Earlier work by Can-Ag Enterprises (1988) estimated that yield reductions in southwestern Ontario on severely compacted soils were around 25%, based on farmers reported yields.

Contrary to these results, research conducted by Stewart and Vyn (1991), at the Elora Research Station, found that corn grain yields were generally not negatively affected by the higher soil resistances and densities in the 0 - 35 cm depth interval. Onwualu and Anazodo (1989), suggest that a medium level of soil compaction is beneficial to corn growth and yield. A possible explanation for this is that medium compaction combined the advantages of better moisture storage and seed bed germination with only moderate resistance to root growth. Obviously, the available soil moisture plays an important role in any of these results as higher crop yields are generally associated with greater amounts of water available in the soil.

The purpose of subsoiling is to open up an area that is permeable to the roots so that they may grow through the compacted region and into the better structured subsoil, where they

can extract water and nutrients. Sene et al. (1985), found that, without subsoiling, a large proportion of roots remain in the Ap horizon during most of the growing season, and therefore, yields in the non-subsoiled fields depend on the amount of available water and nutrients in the Ap horizon. It has been noted by several researchers, that increased yields have been attributed to those cultural practices that decrease soil strength and increase the limits of root exploration (Gerard et al. 1982; Ide et al. 1984; Peterson et al. 1984).

Numerous subsoilers are now found on the market, each with different shank designs. The various shapes contribute to different degrees of soil disturbance. Each design attempts to disturb as much soil as possible with the least draught requirement. Busscher et al. (1988), noted that the advantage of the larger areas of shattering would be a larger area for the roots to explore and penetrate through to the softer subsoil. The advantage of the smaller area is a lower power requirement for the pulling tractor and therefore, a lower energy cost. Each can have a significant economic impact.

The frequency of the subsoiler operation is another common question. Threadgill (1982) and Busscher et al. (1986), found that one year after planting soils can reconsolidate to the point that they can be root restricting. Two years after subsoiling, traces of the subsoil slots were hard, if not impossible to identify. Busscher and Sojka (1987), working in a weakly structured loamy sand could see residual effects on soil strength patterns in the year after subsoiling. However, the strength of the year-old subsoil trench (50-60 cm) was root-limiting and with the planter, in the following year, being unable to directly plant over the trench the roots had to grow laterally before entering the old subsoil trough.

Threadgill (1982) also working on a sandy loam looked at three tillage systems: in row subsoiling at time of planting (36-38 cm) followed by no-till operations; subsoiling followed by moldboard plowing (25-28 cm), and moldboard plowing only. His results indicate that subsoiling greatly reduced the compaction layer beneath the row and an area (7 cm) to each side of the row, but did not effect the compaction in between the rows. Subsoiling with the no-till operation showed no evidence of the subsoiling operation by the end of that growing season. The subsoiling/moldboard plow tillage system did not recompact the subsoil trenches to restrictive cone index levels. However, the continued use of the moldboard plow in the following two years did eliminate the subsoil trenches and reestablish a compacted layer at the plow depth. The moldboard only system supported the general concept that wheel traffic causes severe compaction beneath the tracks with maximum compaction levels occurring at depths equal to 0.5 to 1.0 wheel width.

Both the Threadgill (1982) and Busscher et al. (1986) studies indicate the need for annual subsoiling to provide a beneficial root zone. On the other hand, Duval et al. (1989),

working with a clay soil in Quebec, examined plots ten years after subsoiling and found residual effects still existed. The history of the treatments following the initial operations included five years of no-till silage corn, one year of sugar beets, then four years fallow. After this period they observed significant differences in mottling (an indication of imperfect drainage) and soil structure between treatments.

There was a decrease in mottling as well as an increase in the ability of the soil structure to break into peds for the compacted then subsoiled treatment compared to the compacted only treatment. They concluded that subsoiling of a compacted clay soil can be a long-term benefit to its soil structure.

It is obvious that greater insight is needed into soil and crop response after fall subsoiling in order to better understand the dynamics of this type of soil management. Hence, this study was undertaken to determine if there were any beneficial soil changes from the various subsoiling implements used, if there were any increases in crop yields, to determine if soil quality improved, and to investigate if there was any reduction in water and sediment runoff.

2.0 MATERIALS AND METHODS

2.1 EXPERIMENTAL DESIGN

Thirteen farmers participated in this statistically based, field-scale subsoiling study. Three or four treatments (each with two replicates) were established in fall 1989, after soybean or winter wheat harvest. Treatment plots were marked out in field length strips prior to subsoiling. The four treatments were: Strohm aerator® (1), B.C. Sub-mulcher® (2), Control (3), and Paratill® (4); though not all were included at all sites (as indicated in Table 1). Subsoiling was 25 to 35 cm deep. The strips varied from 10 to 20 m which allowed one or two rounds of a harvester to determine yields. Headlands were omitted to avoid field edge effects. The treatments were replicated twice at each site. The site maps for each farm indicating treatment layout and locations of inspection pits are included in Appendix D.

2.2 SUBSOILING IMPLEMENTS

As mentioned earlier, the study had incorporated three different subsoilers, each with a notably different shank design. The Tye Paratill® had a leg designed with a 45° angle to lift the soil (Figure 2). The Strohm aerator® was equipped with wings on both sides of the shank to lift the soil (Figure 3). The B.C. Sub-mulcher® had a narrow angled shank to shatter the compacted layer (Figure 4).

The first four sites were subsoiled with the computerized tractor from Agriculture Canada Research Centre in Ottawa (Figure 5). The instrumentation incorporated into this specialized tractor provided data on numerous aspects of a tillage operation. For this report, only the fuel consumption and draught results for each of the three implements were used.

The remaining sites were subsoiled by either the farmer (four sites) or by a tractor and technician (six sites) supplied by the Agriculture Canada Research Station in Harrow.

2.3 CLIMATIC RECORDS

Co-operators were supplied with record sheets to keep track of precipitation and significant events (ie. thunderstorms, high winds, hail, etc.). This information assisted in providing answers to anomalies in crop growth between locations. The climatic data listed in this report were supplied by Ridgetown College.

Table 1. List of Co-operators (Site No.), Implements Used, and Level of Detail of Data Collection.

CO-OPERATOR	IMPLEMENTS	LEVEL OF DETAIL*
Bee, Ken (1)	Paratill®	1, 2
Bradley, Brock (2,3)	Field 1: B.C. Sub-mulcher® Strohm aerator® Paratill® Field 2: B.C. Sub-mulcher® Strohm aerator®	1, 2
Cumming, Peter (4)	B.C. Sub-mulcher® Strohm aerator® Paratill®	1, 2, 3
Farquharson, Robert (5)	B.C. Sub-mulcher® Strohm aerator®	1, 2, 3
Hoy, John (6)	B.C. Sub-mulcher® Strohm aerator®	1, 2
Jack, Murray/ Johnstone, Bruce (7)	B.C. Sub-mulcher® Strohm aerator® Paratill®	1, 2, 3
Jack, Robert & Glen (8)	B.C. Sub-mulcher® Strohm aerator®	1, 2
Parry, Douglas (9)	B.C. Sub-mulcher® Strohm aerator®	1, 2
Parry, Garfield (10)	B.C. Sub-mulcher® Strohm aerator®	1, 2
Parry, Mark (11)	B.C. Sub-mulcher® Strohm aerator® Paratill®	1, 2
Skipper, Brian (12)	B.C. Sub-mulcher® Strohm aerator® Paratill®	1, 2, 3
Vince, Elwin (13)	B.C. Sub-mulcher® Strohm aerator® Paratill®	1, 2, 3
Wonnacott, Stanley (14)	B.C. Sub-mulcher® Strohm aerator® Paratill®	1, 2, 3

* 1 visual soil evaluation
2 visual soil evaluation + 2 penetrometers B.D. control
3 visual soil evaluation + 2 penetrometers all B.D's in 1 rep.

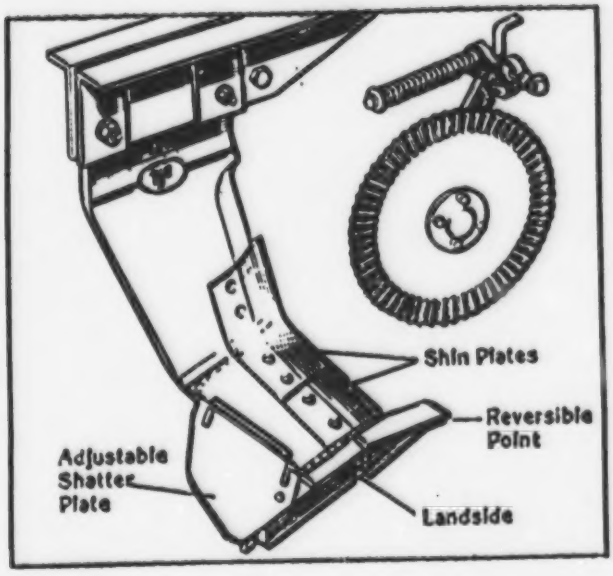


Figure 2. Tye Paratill®.

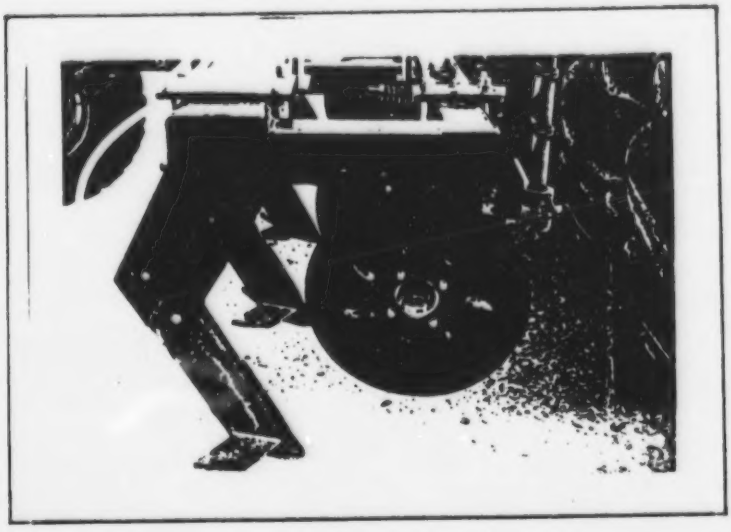


Figure 3. Strohm aerator®.

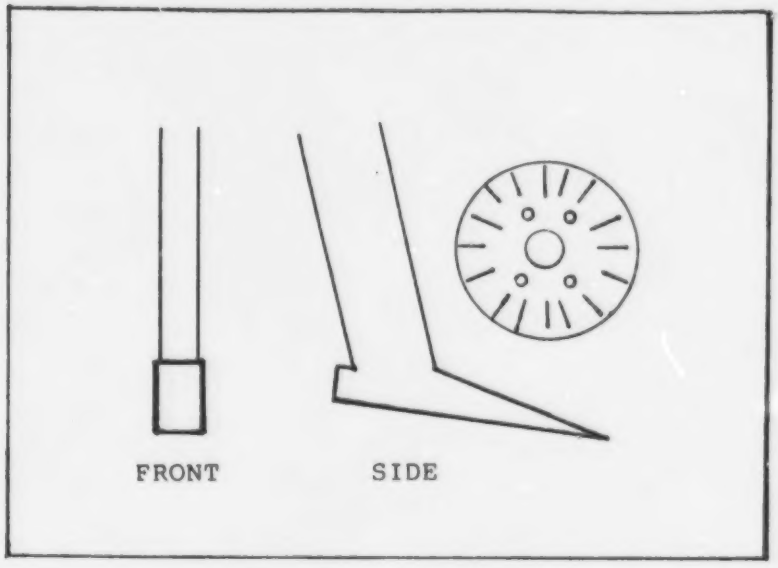


Figure 4. B.C. Sub-mulcher®.

Figure 5. Agriculture Canada's computerized Research Tractor pulling the Paratill®.

Figure 6. Observation pit - Visual Assessment.

2.4 FIELD INVESTIGATIONS

Field investigations included visual assessments and measurements of soil parameters indicative of soil compaction. Soil samples were taken at the time of subsoiling to determine soil moisture content. After the subsoiling was completed the soils were examined at two or three levels of detail to describe and measure initial conditions. First a visual assessment (first level of detail) was made inspecting soils to 50 cm at three sites within each plot focusing on: soil uniformity, degree and depth of compaction, soil structure and pore description, horizon depths, hand texture, drainage and topography (slope, position) (Figure 6). The visual descriptive techniques were identical to those used in the past Can-Ag compaction studies (Tables 2 and 3). The data collected focused on three depth intervals, roughly 0 to 20, 20 to 30, and 30 to 40 cm representing the A horizon (topsoil or plow layer); the AB horizon (includes lower A and or upper B and often compacted layer); and the B horizon (below the compacted or potentially compacted layer). The middle and representative pit (1 m width) (Figure 7) in each plot was investigated with a second level of detail noting the above plus taking penetrometer (both pocket, Figure 8 and Dickey-john®, Figure 9) measurements to 48 cm depth. Bulk densities were taken for the control only (Figure 10).

The third level of detail includes the above as well as bulk density in two to three soil layers. The majority of sites where plowed and therefore had a disturbed Ap thus eliminating the bulk density from the top horizon. These intensive measurements were completed for all treatments of one replicate at six sites (indicated in Table 1).

A subsoiler evaluation rating was given for the three subsoilers at all the sites. The specific rating for subsoiler performance was developed by determining the percentage of soil disturbance in a one metre wide section of the AB layer. The extent of loose or shattered soil was measured from the shank penetration point. The B.C. Sub-mulcher® and the Strohm aerator® had 76 cm spacing between shanks, while the Paratill® had 66 cm spacing on the side shanks and a 109 cm centre gap where the two interior shank ends angle inwards. The metre wide observation section was centered on a shank entry point and therefore, included one shank and possibly some shattering from the adjacent shank.

The second year observations also had a subsoiler rating, but it was based on any residual effects of the subsoiler shank in a metre wide observation section. This was determined visually as well as probing the observation pit walls for areas of loose soil structure and was given either a 'yes' or 'no' rating.

Table 2. Simple System for Describing Soil Macrostructure (from McKeague, et al., 1986).

I			Lacks an organized system of macrovoids and peds.
	1.*	IA	The material is massive and coherent.
		IB	The material is loose or single-grained.
II			Has a system of more-or-less vertical, tubular voids (channels) in apedal material.
		IIA	Channels 0.5 mm or larger in diameter occupy 0.1 to 0.5% of the volume of tubular voids can be estimated by using dot charts.
		IIB	Channels as specified above occupy more than 0.5% of the volume.
III			A system of more-or-less vertical cracks traverses the horizon; horizontal planar voids are weakly-developed or absent.
		IIIA	The cracks occupy less than 1% of the volume and vertical channels larger than 0.5 mm occupy less than 0.1% of the volume. (Volume of cracks can be estimated by measuring the total width of cracks in a 1 m transect; for example, four cracks 2 mm wide in 1 m would indicate crack volume of 0.8%).
		IIIB	The cracks occupy more than 1% of the volume or cracks occur but occupy less than 1% of the volume and channels larger than 0.5 mm occupy more than 0.1% of the volume.
IV			A system of more-or-less horizontal planar voids partially or completely divides the material into platy units with less than 0.1% vertical tubular voids.
	2.	IVA	Planar voids are weakly expressed.
	2.	IVB	Planar voids are strongly expressed.
V			A system of planar voids in more-or-less horizontal and vertical directions partly to completely separates the material into blocky or prismatic peds with less than 0.1% vertical tubular voids.
	3.	VA	The planar voids are weakly developed and the partly-formed peds adhere.
	4.	VB	A well developed planar void system separates most of the material into peds.
VI			Vertical tubular voids occupy 0.1 to 0.5% of the volume and systems of vertical and horizontal planar voids occur.
	5.	VIA	Planar voids are weakly developed and the partly-formed platy, blocky or prismatic peds adhere.
	6.	VIB	Planar voids are well developed and most of the material occurs as peds.
VII			Vertical tubular voids occupy more than 0.5% of the volume and systems of vertical and horizontal planar voids occur.
	7.	VIIA	Planar voids are weakly developed and the partly-formed peds adhere.
	8.	VIIB	Planar voids are well developed and most of the material occurs as peds.

* Number denotes ranking used in correlation analysis.

Table 3. Soil Compaction Indicators: Subjective Rating (from Can-Ag Enterprises, 1988).

Compaction Indicators	Slight	Moderate	Severe
Structure	moderate to strong granular or subangular blocky	layered, deformed	massive, structureless, clods
Consistence	very friable or friable in A horizon, friable to firm in B horizon	firm in A & B horizon	very firm in A & B horizons
Soil pores	abundance of planar and tubular pores	few tubular pores, horizontal planar voids	lack of tubular & planar pores
Root Distribution	normal distribution of inped and exped roots	deformed rooting pattern	distinctive decrease in abundance in compact layer relative to layer above, root mat above compact layer
Earthworms	moderate to plentiful	few to moderate	none
Soil Water	uniform moisture distribution, little or no ponding after rains	restricted water percolation	surface ponding or ponding above compact layer after rains
Uniformity	above features found at all spot checks	above features variable	most above features observed at all spot checks

Figure 7. Investigation pit - Second and Third Level of Detail.

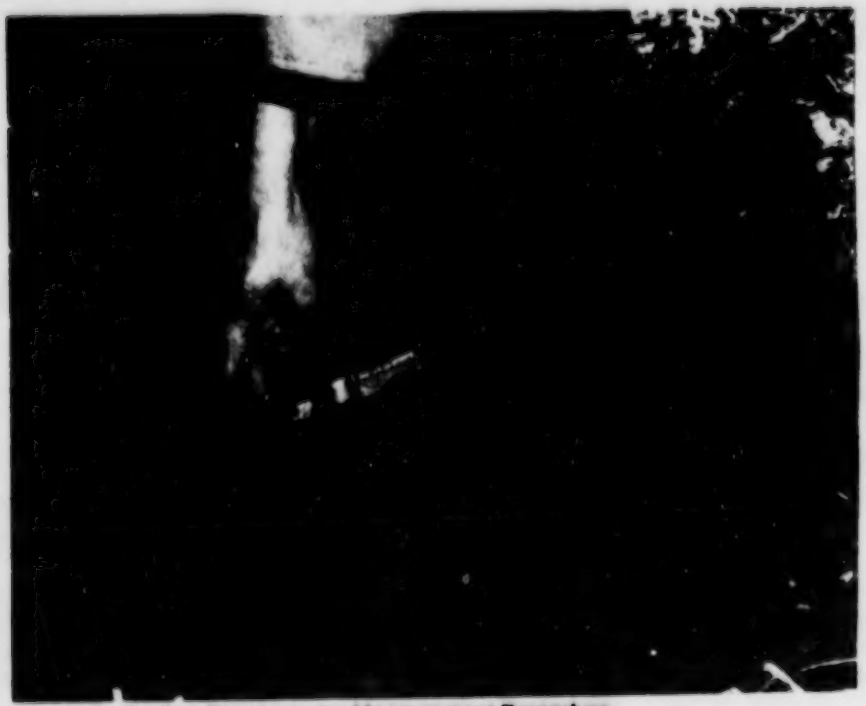


Figure 8. Pocket Penetrometer Measurement Procedure.

Figure 9. Dickey-john® Penetrometer Measurement Procedure.

Figure 10. Bulk Density Coring Procedure.

From each field, composite samples of the three layers were taken to determine soil pH, nutrient levels and organic matter content. Particle size analysis was done for the six intensive sites. All sampling site locations were recorded using a measuring wheel and markers at the field edge in order to permit resampling near the original sites in the second year.

Several visits to the sites were made during the growing season to note any differences in emergence, mid-season growth, and late season maturity among the treatments. Important soil indicators such as ponding, soil cracking, rutting and crop moisture stress where also recorded.

Weigh wagons were supplied to the farmers so yields could be determined for each replicate and treatment. After harvest, the soil investigations were initiated. These investigations were identical to the first year with the only difference being the elimination of the particle size analysis which would be redundant in the second year.

2.5 STATISTICAL ANALYSES

1989

There were two principle methods of statistical analyses performed. The first method employed the use of CoStat® to perform an analysis of variance (ANOVA) procedure to establish if significant differences exist among the different subsoiling treatments with respect to the measured soil properties ($P=0.05$) (see Appendix A for input data). The Duncan's Multiple Range Test (DMRT) was used to test the similarity of all pairs of means and organize the means into groups of non-significantly-different means ($P=0.05$) (CoStat® manual, 1986).

Secondly, a Pearson correlation matrix (PCM) was constructed to determine if measurable significant correlations exist among the various soil parameters measured ($P=0.05$) (see Appendix A for input data). A significant positive correlation indicates that as a parameter increases, the one it is being compared with is also expected to increase at least 95 percent of the time. A significant negative correlation indicates that as the level of one factor increases, the level of the other is expected to decrease. A cause and effect relationship is not implied, although it may exist, and there are often important interactions among various factors that complicate the interpretations. These are discussed later in the report.

Additional statistical analyses were performed for comparison between types of implements and between passes with respect to fuel consumption (L/ha) and draught in Newtons (N) using data gathered from the Agriculture Canada research tractor on treatment plots located at three sites (#11, 12 and 14). Data gathered from Site 7 were not included in analyses because only two shanks (instead of four) were pulled through the soil by the implements. Analyses of these data were completed with the use of t-tests (CoStat®).

Also, correlation analysis was completed for each of the three fields and implements to determine if any relationships exist between draught required to pull the implements and fuel consumption.

1990

As in 1989, generally two methods of statistical analyses (ANOVA AND PCM'S) were performed. Using Costat® Software, analysis of variance procedures were conducted to establish if significant differences exist between certain ranges in soil depth as well as between the various subsoiling treatments with respect to certain soil compaction measurements. ANOVA was also used to discriminate any differences in soil compaction between the years 1989 and 1990 with respect to the measured soil properties (pocket penetrometer readings and bulk density measurements). Differences in 1990 corn and soybean yields with regards to the various subsoiling treatments performed in 1989 were also examined using ANOVA. The Duncan's Multiple Range Test was again used to test the similarity of all pairs of means. Additional statistical analyses employed paired t-tests used to examine if significant differences exist between 1989 and 1990 with respect to compaction (ie. analysis of Dickey-john® as well as pocket penetrometer readings, bulk density, and compaction ratings) for all sites.

Two Pearson correlation matrices were completed for the 1990 data. The first matrix was performed to determine if measurable significant correlations exist among soil fertility values and crop yields ($P = 0.05$). The second matrix was completed to determine if correlations could be detected among the soil physical properties measured, loading values, and yields ($P = 0.05$) (see Appendix B for input data).

2.6 FARMER INTERVIEWS

Co-operating farmers were interviewed after each year of research (1989 and 1990) the following January to obtain information about their farming operations on the test sites. In general, information was gathered concerning their land management practices, in addition to their assessment of soil quality and severity of compaction. Details on cropping and fertilizer practices (including fertilizers used and rates of application), number and types of field operations, and fall tillage depth were recorded. Information regarding machinery encompassed the types of tractors used, horsepower, and weights (if known), size and number of rear wheel tires, and types of implements used and their widths.

The questionnaire supplied for the second year had specific questions on the soil conditions and crop growth encountered in the 1990 season. The farmer was asked to note any differences in ease of spring tillage, soil surface drainage, plant emergence and development, observed yield differences and ease of fall tillage. The data provided by the computerized Agriculture Canada tractor provided an indication of fuel requirements for each subsoiling implement.

3.0 RESULTS

3.1 CLIMATIC CONDITIONS

The 1990 growing season moisture supply was slightly below the 30 year average during April through June and above average during July through October. Heat units were lower than average in May but similar the rest of the season. Soil conditions were moist in the spring and conducive to compaction. Mid summer growing conditions were excellent. Moist soils in the fall were again prone to compaction.

Thus, fall subsoiling was performed in slightly moister conditions then was ideal, yet this was typical of the conditions a farmer might experience. The percent soil moisture at the time of subsoiling in the fall of 1989 was compared to the spring subsoiling in the dry year of 1988 with the Can-Ag previous study. There was little change in the lower horizons. In 1988, soil samples were taken at 7.6, 17.8, and 30.5 cm depths. The average of 7.6 and 17.8 cm was 19.7%, and the average of 17.8 to 30.5 cm depths calculated out to be 24.3%. In 1989, the 0-15 cm average was 26.1% and the 15-30 cm depth was 25.3%.

In the spring of 1990 the weather caused emergence problems on a large number of fields in Kent County. The problems arose from a combination of cool soil temperatures at planting, extensive rainfalls after planting, followed by warm weather to create an impenetrable crust that restricted young plants from emerging. The slow emergence not only hindered development, but left the seedlings vulnerable to slug damage.

Both corn and soybeans were affected by the 1990 spring conditions, yet among our fourteen sites, only two fields had to be replanted, one corn and one soybean (spot planted). Several other soybean fields lagged behind in development because of the poor start. Mid-summer weather provided some excellent growing conditions, though a few areas of Kent County experienced some drought problems.

Excessive rain in the fall 1990 created extremely moist soil conditions at harvest time. However, only at one site was deep rutting from harvest equipment noted. Table 4 provides the precipitation and heat unit data for Kent County recorded at Ridgetown College for the 1990 growing season as well as the 30 year average.

3.2 FIELD OBSERVATIONS DURING THE GROWING SEASON

The only noticeable difference that several farmers observed was less ponding on the subsoiled areas. Yet the surface water noted on the controls did not have any impact on the yields for these treatments. No differences in fall or spring tillage where experienced and only

Table 4. Kent County Climatic Data.

MONTH	1990 PRECIPITATION (mm)	30 YEAR AVERAGE (mm)	1990 HEAT UNITS	30 YEAR AVERAGE
April	44.1	81.2	-----	-----
May	71.0	73.3	280.16	341.8
June	47.0	81.4	689.2	674.3
July	93.0	85.1	792.8	804.1
August	145.2	98.9	770.7	781.2
September	123.4	84.6	566.3	589.8
October	64.3	57.9	243.9	172.0

one farmer noted an emergence difference, observing a slightly better start on the Paratill® treatment.

A Can-Ag technician visited the sites three times throughout the growing season: at emergence, in late June, and in early August. On each of these visits, the technician could not clearly identify any crop difference relating to subsoiling, between treatments. Differences were noted within a treatment, which were probably caused by other factors (ie. fertilizer placement, herbicide effectiveness, soil type, etc.) No ponding was recorded for any of the treatments (visits were not immediately after any rain events), but some rutting was noticed after fall harvest for the Paratill® treatment in a no-till field.

3.3 SOIL COMPACTION OBSERVATIONS

In the first year, data collected from the inspection pits for the three layers (A, AB, B) showed that most soil disturbance resulted from the Paratill® treatment followed by the Strohm aerator® and the B.C. Sub-mulcher®, respectively. This was indicated by the lower penetrometer readings and greater amounts of soil pores and worms (means shown in Table 5) in the Paratill® treatment. Detailed data are presented in Appendix A.

In the second year, only a few sites had obvious residual effects of the subsoiling operations. These sites were all under a conservation tillage program and therefore, fall tillage did not include moldboard plowing. Where the effects of subsoiling were obvious, the soil in and immediately surrounding the shank patch was looser and considerably higher in moisture.

Table 5. 1989 Soil Compaction Measurements.

Soil Parameter	Subsoiling Treatment			
	1 (Strohm aerator®)	2 (B.C. Sub-mulcher®)	3 (Control)	4 (Paratill®)
Dickey-john® penetrometer readings (lbs/in²)	n=24	n=24	n=26	n=14
DJ1 (0- 8 cm)	108 a*	108 a	125 a	96 a
DJ2 (8-16 cm)	164 a	170 a	266 a	160 a
DJ3 (16-24 cm)	226 bc	234 b	262 a	207 c
DJ4 (24-32 cm)	293 b	299 b	324 a	282 b
DJ5 (32-40 cm)	346 a	356 a	372 a	362 a
DJ6 (40-48 cm)	374 bc	381 b	393 a	368 c
Pocket penetrometer readings (kg/cm²)	n=24	n=24	n=26	n=14
POA	---	---	---	---
POAB	2.25 c	2.49 ab	2.66 a	2.27 bc
POB	2.28 ab	2.36 a	2.48 a	2.08 b
Bulk density readings (g/cm³)	n=12	n=12	n=27	n=10
BDA	---	---	---	---
BDAB	1.47 a	1.47 a	1.48 a	1.52 a
BDB	1.54 a	1.51 a	1.53 a	1.57 a
Worms	n=26	n=26	n=28	n=16
WA	2.38 a	2.15 a	2.14 a	2.31 a
WAB	2.31 ab	2.19 ab	2.07 b	2.44 a
WB	2.38 a	2.23 a	2.32 a	2.5 a
Pores	n=26	n=26	n=28	n=16
PA	8.0 a	7.96 ab	7.86 bc	7.81 c
PAB	6.12 ab	5.77 bc	5.46 c	6.31 a
PB	7.42 a	7.31 a	7.43 a	7.56 a

*Note: for all soil parameters, values followed by the same letter in each row are not significantly different (ANOVA, DMRT, $\underline{P}$=0.05); for DJ1 only n=16 (trmt 1), n=15 (trmt 2), n=18 (trmt 3), n=9 (trmt 4) (see Appendix C for explanation of parameter codes).

These observations were noted most frequently with the Paratill®, then the Strohm aerator®, followed by the B.C. Sub-mulcher®.

An interesting observation noted during the first year's soil investigation (1989) was the depth of plowing that some of the farmers were performing. Plowing to 30+ cm and in one case bringing up the subsoil virtually eliminated the effects of subsoiling at a few sites. Yet there was no obvious amount of increased compaction in the B layer. The soil investigations for the second year were performed before fall tillage at the majority of sites. Where the field was shallow plowed, in the previous fall (1989), there was a definite compacted layer below the plow layer. Where the soils had been deep plowed to the bottom of the A-B interface, there was not as much compaction beyond the plowed layer. This last point agrees with the observations from the first year. Therefore, the B horizon of the heavier clay soils, which already has a relatively high bulk density, did not compact much more. This means the naturally created voids found in this horizon remain intact under additional loading. The A horizon on the other hand can compact to a bulk density value similar to the B horizon. Yet in this case, the naturally occurring voids will be significantly altered (compacted) under additional loads, therefore, reducing the amount of water infiltration. This was quite obvious at several sites where the bottom of a shallow plowed layer had excessive amounts of water unable to infiltrate the compacted layer below. No excessive amounts of water were found where the soil was deep plowed to the A-B interface.

In a fall moldboard plowing situation, subsoiling did not appear to be beneficial. The zone with the remaining subsoiler trench was so small (especially with deep plowing) that the benefits of the subsoiling operation would be lost. Subsoiling performed at planting or shortly thereafter may contribute more to plant development as the plant recovers the benefits, without tillage disturbance, throughout the growing season. This suggestion is supported in the severely compacted soils of the previous Can-Ag study (1988). Fields managed under a conservation tillage program (ridge till, no-till, or soil saver) could receive the proposed benefits of subsoiling at least for one year.

3.4 1989 EFFECTS OF SUBSOILING TREATMENTS ON SOIL PROPERTIES

Autumn measurements of soil properties on each treatment included Dickey-john® penetrometer readings (vertical), pocket penetrometer readings (horizontal), bulk densities, abundance of earthworms, and number and size of soil pores. Average values and statistical significance are summarized in Table 5.

As expected vertical penetrometer readings indicated greater resistance as soil depth increased. For soil depths of 16 to 24, 24 to 32, and 40 to 48 cm, control treatments had consistently greatest resistance to the penetrometer (F=7.28; df=3,32; P=0.0007), (F=5.48; df=3,32; P=0.0037), and (F=6.36; df=3,2; P=0.0017), respectively. Resistances in the Paratill® treatments were consistently lowest for all readings. At all depths, there were no measurable differences in resistance between the Strohm aerator® and B.C. Sub-mulcher® treatments. At the 16 to 24, and 40 to 48 cm depths, vertical penetrometer resistances in the Paratill® treatments were significantly less compared with those recorded in the B.C. Sub-mulcher® treatments.

Pocket penetrometer readings revealed a similar pattern. In both the compact (AB) and subsoil (B) layers, control treatments continued to show the greatest soil resistance (Table 5). The Strohm aerator® and Paratill® treated plots had the least resistant ratings in the compact (F=4.92; df=3,30; P=0.0067) and subsoil (F=3.36; df=3,32; P=0.0307) layers. In general, all penetrometer readings indicated improved soil conditions following subsoiling.

Bulk density measurements, not unexpectedly, increased with greater soil depth. There were no measurable differences in bulk density values between subsoiling treatments in either the compact or subsoil layers.

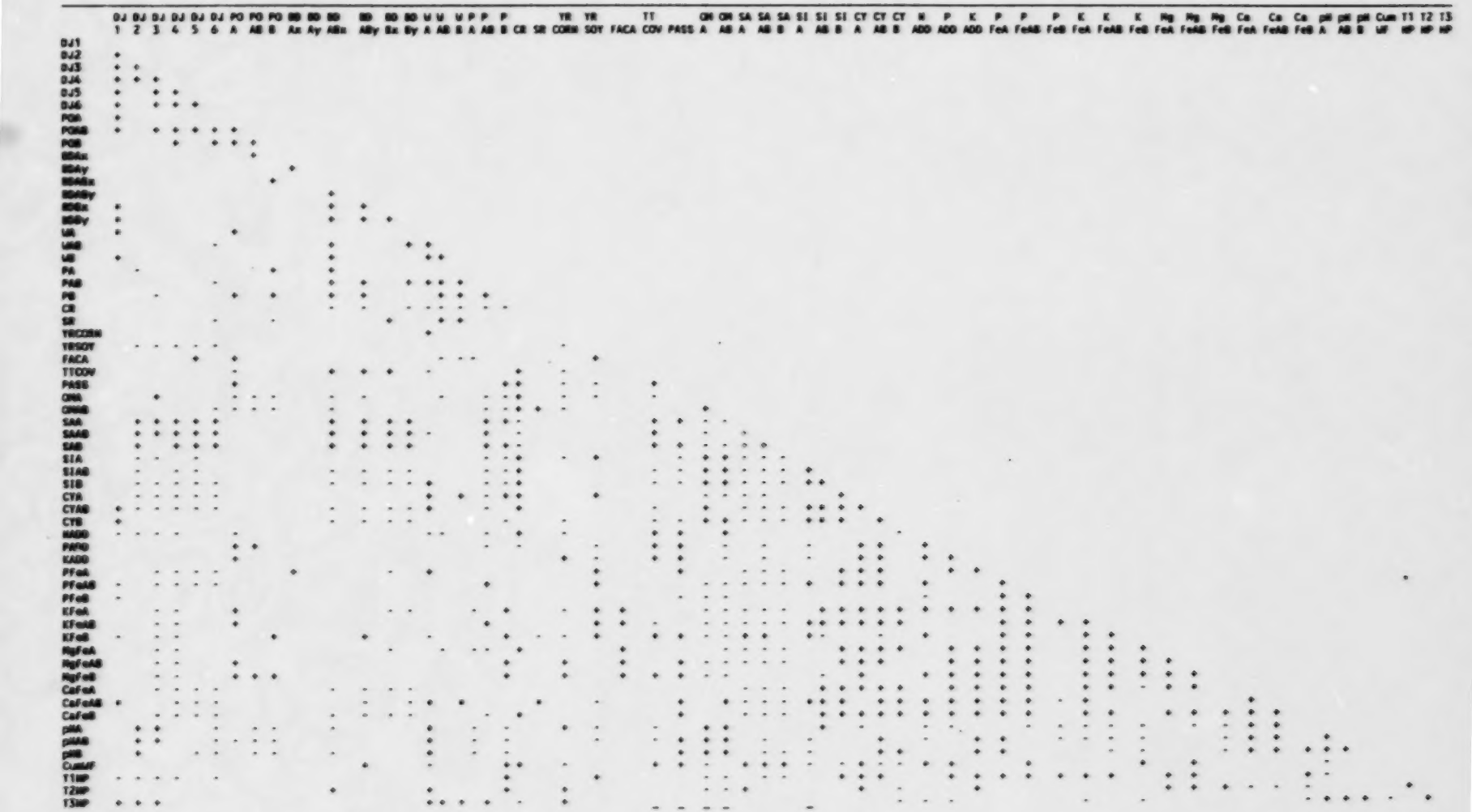
Earthworm abundance did not differ with respect to subsoiling treatments in the topsoil, compact or subsoil layers. However, the occurrence of pores in the soil improved with subsoiling in the topsoil (F=3.37; df=3,40; P=0.0277) and compact (F=3.70; df=3,40; P=0.0193) soil layers (Table 5).

3.5 1989 RELATIONSHIPS AMONG SOIL PROPERTIES AND MANAGEMENT FACTORS

It was observed (from the correlation matrix) that verticle penetrometer readings (DJ1 to DJ6, representing the different depths) were generally positively correlated with each other (Table 6). They were also positively correlated with percentage sand, but negatively associated with silt and clay content of the soil. Pocket penetrometer readings closely matched the Dickey-john® penetrometer readings, and they were strongly negatively correlated with percentage organic matter.

Bulk density values of different soil layers (A, AB, B) were generally positively correlated with each other. As well, in the compact (AB) layer, there was a positive correlation with the presence of worms and soil pores. With greater bulk density, there was more associated sand, and less silt and clay in the soil.

Table 6. 1989 Pearson Correlation Matrix.



Not unexpectedly, the abundance of worms was positively correlated with the occurrence of soil pores. There was also a positive relationship with percentage clay and with soil pH levels (Table 6).

There was a strong negative relationship between abundance of worms and soil compaction (CR) ratings. As pore space (AB and B layers) increased, the data show that organic matter content declined, that there is greater percentage sand and less silt content.

Compaction ratings of all fields were positively correlated with silt and clay content, with total tractor tire coverage (per year calculated on a percentage basis), with the number of passes, and with cumulative loading (see Appendix C for full explanation of parameters). Negative correlations existed with worms, pores, and bulk density ratings (compact layer). There was also a negative relationship with sand content. Subsoiling ratings (SR) were positively correlated with abundance of worms and organic matter (compact layer), and negatively correlated with pocket penetrometer resistance readings (subsoil layer).

Average 1985 to 1989 corn yields on test fields as reported by farmers showed some positive relationships with abundance of worms and soil reaction (pH) in the topsoil, additions of potassium fertilizer, and soil magnesium levels. Several negative correlations existed with organic matter content, silt present in A layer, clay in B layer, nitrogen fertilizer additions, potassium levels, number of passes, total tire coverage, and cumulative tractor loading.

Average soybean yields from 1985 to 1989 on these test sites as reported by farmers increased with presence of silt and clay in topsoil, and phosphorous and potassium fertility levels. With increased yields, there are associated declines in soil resistance ratings (Dickey-john®), organic matter, phosphorous and potassium fertilizer additions, pH, and in number of passes. There were associated increases in yield of corn and soybeans with phosphorous, potassium and magnesium soil fertility levels (Table 6).

From these data, when corn and soybean yields were compared, it was apparent that corn was more sensitive to compaction stress, and yields seemed to decline with more activity in the field. There were no apparent relationships between average soybean yields and compaction rating, total tire coverage, or cumulative loading.

Greater organic matter content was associated with less penetrometer resistance (pocket), a decline in bulk density (AB layer) and soil pores, increases in silt and clay, as well as decreased sand content. There were also positive correlations between organic matter with soil reaction (pH), compaction ratings (CR), and subsoiling ratings (SR).

Rates of fertilizer applied in 1989 and inherent nutrient levels in soils sampled in the autumn (as determined by routine soil analyses) were mentioned above in connection with several factors. The highlights were as follows. Increased nitrogen, phosphorous, and

potassium rates matched increases in total tire coverage and number of passes. This is not, however, reflected in increased penetrometer resistance, nor in bulk density ratings. The 1989 rates of fertilizer application (phosphorous and potassium) were positively correlated with levels of nutrients in the soils. Nutrient levels in the soils were positively correlated with silt and clay content. There was a negative relation with sand content, organic matter, pH, and penetrometer resistance (phosphorous and calcium only).

Soil reaction (pH) was positively correlated with abundance of worms in the topsoil, organic matter content, clay content (compact and subsoil layers), with nutrient levels as well as number of passes. It was negatively correlated with pocket penetrometer resistance ratings, pore space, and potassium fertility levels in the soils.

Field operation considerations which included type of tractor used (T1HP, T2HP, T3HP), total tire coverage (TTCov), number of passes (PASS) on the field (based on width of implement used), and cumulative tractor loading (Cum WF) were recorded and/or calculated for 1989 (Table 6).

There were positive significant correlations between tractor size and five-year average corn yields. Total tire coverage and cumulative loading were strongly positively correlated with soil parameters associated with and contributing to soil compaction, thus having a detrimental influence on abundance of earthworms in topsoil and on average corn yields.

Several of the soil property relationships were questionable. These included: a positive correlation between bulk density and presence of worms and soil pores; a negative correlation between compaction ratings and bulk density values and a negative correlation between yields and organic matter.

3.6 1990 EFFECTS OF SUBSOILING TREATMENTS ON SOIL PROPERTIES

Autumn measurements of soil properties on each treatment included Dickey-john® (vertical) and pocket (horizontal) penetrometer readings, bulk densities, abundance of earthworms and number and size of soil pores. Mean values and statistical significance for comparisons between soil depths for these parameters are summarized in Table 7. Each of the eight sites (#1, 2, 4, 7, 11, 12, 13 and 14) used contained the four subsoiling treatments with the exception of site #1 (Control and Paratill® only).

As expected, vertical penetrometer readings indicated significantly greater resistance as soil depth increased in each subsoiling treatment. Pocket penetrometer readings revealed the greatest resistance to soil penetration in the compact layer, and the least resistance to be in the topsoil layer. This was especially noted in the control treatments ($F=227.1$; $df=2,251$; $P=0.0000$) where the topsoil had a pocket penetrometer reading of 1.34 kg/cm^2 and a compact

Table 7. 1990 Soil Compaction Measurements (Comparison Between Soil Depths).

Soil Parameter	Subsoiling Treatment			
	1 (Strohm aerator®)	2 (B.C. Sub-mulcher®)	3 (Control)	4 (Paratill®)
Dickey-john® penetrometer readings (lbs/in²)	n = 84	n = 84	n = 96	n = 96
DJ1 (0- 8 cm)	152 f*	156 e	162 e	153 f
DJ2 (8-16 cm)	211 e	218 d	233 d	216 e
DJ3 (16-24 cm)	273 d	282 c	292 c	257 d
DJ4 (24-32 cm)	341 c	354 b	354 b	316 c
DJ5 (32-40 cm)	377 b	390 a	393 a	369 b
DJ6 (40-48 cm)	396 a	400 a	399 a	394 a
Pocket penetrometer readings (kg/cm²)	n = 84	n = 84	n = 96	n = 96
POA	1.41 c	1.47 c	1.34 c	1.45 c
POAB	2.65 a	2.66 a	2.85 a	2.47 a
POB	2.42 b	2.45 b	2.53 b	2.28 b
Bulk density readings (g/cm³)	n = 10	n = 10	n = 10	n = 10
BDA	1.45 c	1.43 b	1.45 b	1.50 a
BDAB	1.49 b	1.47 b	1.48 ab	1.51 a
BDB	1.57 a	1.55 a	1.50 a	1.53 a
Worms	n = 42	n = 42	n = 48	n = 48
WA	2.71 a	2.79 a	2.56 a	2.54 a
WAB	1.64 c	1.50 c	1.52 c	1.98 c
WB	2.24 b	2.29 b	2.23 b	2.19 b
Pores	n = 42	n = 42	n = 48	n = 48
PA	7.95 a	8.00 a	7.81 a	7.98 a
PAB	6.00 c	5.81 c	5.77 c	6.13 c
PB	7.17 b	7.14 b	7.06 b	7.19 b

*Note: for each soil parameter, values followed by the same letter in each column are not significantly different (ANOVA, DMRT, $P=0.05$). For bulk density, five sites were used (#4, 7, 12, 13, 14). For Dickey-john®, DJ1 and DJ2 n=72 (Strohm aerator® and B.C. Sub-mulcher®), n=84 (Control and Paratill®); for pocket, POA (n=60); for bulk density, BDA (n=6) (see Appendix C for explanation of parameter codes).

layer reading of 2.85 kg/cm². Observations of Dickey-john® and pocket penetrometer measurements were similar to those noted in 1989.

In general, soil bulk density increased with depth. This was most pronounced in the Strohm aerated treatments ($F=21.71$; df=2,25; $P=0.0002$) (Table 7).

Earthworm abundance differed significantly with respect to soil depth in each type of subsoiling treatment. The greatest number of earthworms were rated in the topsoil layer, and the least in the compact layer for every treatment. These were similar to observations noted in 1989. The estimation of the number of pores in the soil revealed the same pattern as earthworm abundance ratings. This could be easily observed for any of the four treatments, but especially for the B.C. Sub-mulcher® where the differences observed between the soil layers were the greatest ($F=505.14$; df=2,125; $P=0.0000$) (Table 7).

Results from the ANOVA used to discriminate if any differences existed between the subsoiling treatments with respect to the various soil parameters were summarized in Table 8. According to the Dickey-john® measurements, significant differences between the subsoiling treatments started at the 16-24 cm depth ($F=4.02$; df=3,59; $P=0.0169$), and were present in lower depths as well. In each range of soil depth, the control treatments had the greatest evidence of soil compaction, and the Paratill® treatments had the least (especially from the 16-24 cm range and lower).

With respect to pocket penetrometer resistance ratings, no significant difference in the A layer was observed between treatments ($F=1.10$; df=3,239; $P=0.3509$). In both the AB ($F=11.54$; df=3,359; $P=0.0000$) and B ($F=7.63$; df=3,359; $P=0.0001$) soil layers, the least compaction was noted in the Paratilled treatments (Table 8).

Bulk density measurements taken were not significantly different with respect to treatments in the A soil layer. However, bulk densities measured in the AB layer showed lower readings in the B.C. Sub-mulched treatments as compared with treatments that were Paratilled. In the B layer bulk density measurements in the control treatments were significantly lower compared with those in the Strohm aerated treatments ($F=3.52$; df=3,39; $P=0.0337$).

The abundance of worms did change significantly in the A layer between subsoiling treatments ($F=8.15$; df=3,179; $P=0.0000$). There were significantly more worms in the Strohm aerated and B.C. Sub-mulched treatments when compared with the Control or Paratilled treatments. In the AB layer, the greatest estimation for the presence of earthworms was observed in the Paratilled treatments ($F=20.42$; df=3,179; $P=0.0000$). In the B soil layer no significant differences between treatments were observed ($F=1.13$; df=3,179; $P=0.3398$).

Table 8. 1990 Soil Compaction Measurements (Comparison Between Subsoiling Treatments).

Soil Parameter	Subsoiling Treatment			
	1 (Strohm aerator®)	2 (B.C. Sub-mulcher®)	3 (Control)	4 (Paratill®)
Dickey-john® penetrometer readings (lbs/in²)	n = 14	n = 14	n = 16	n = 16
DJ1 (0- 8 cm)	152 a*	156 a	162 a	153 a
DJ2 (8-16 cm)	211 a	218 a	233 a	216 a
DJ3 (16-24 cm)	273 ab	282 a	292 a	258 b
DJ4 (24-32 cm)	341 a	354 a	354 a	316 b
DJ5 (32-40 cm)	377 bc	390 ab	393 a	369 c
DJ6 (40-48 cm)	396 ab	399 a	399 a	394 b
Pocket penetrometer readings (kg/cm²)	n = 84	n = 84	n = 96	n = 96
POA	1.41 a	1.47 a	1.34 a	1.45 a
POAB	2.65 b	2.66 b	2.85 a	2.47 c
POB	2.42 a	2.45 a	2.53 a	2.28 b
Bulk density readings (g/cm³)	n = 10	n = 10	n = 10	n = 10
BDA	1.45 a	1.43 a	1.45 a	1.50 a
BDAB	1.49 ab	1.47 b	1.48 ab	1.51 a
BDB	1.57 a	1.55 ab	1.50 b	1.53 ab
Worms	n = 42	n = 42	n = 48	n = 48
WA	2.71 a	2.79 a	2.56 b	2.54 b
WAB	1.64 b	1.50 c	1.52 bc	1.98 a
WB	2.24 a	2.29 a	2.25 a	2.19 a
Pores	n = 42	n = 42	n = 48	n = 48
PA	7.95 a	8.00 a	7.81 b	7.98 a
PAB	6.00 ab	5.81 bc	5.77 c	6.13 a
PB	7.17 a	7.14 a	7.08 a	7.17 a

*Note: for all soil parameters, values followed by the same letter in each row are not significantly different (ANOVA, DMRT, P=0.05). For bulk density, five sites were used (#4, 7, 12, 13, 14). For Dickey-john®, DJ1 and DJ2 are n=12 (Strohm aerator® and B.C. Sub-mulcher®), n=14 (Control and Paratill®); for pocket penetrometer, POA is n=60; for bulk density, BDA is n=6 (see Appendix C for explanation of parameter codes).

In general, since many of the pores are attributable to earthworms, it follows that observations for the number of pores in the soil follow a pattern similar to that for earthworms (Table 8). In the A soil layer there was significantly more soil pores noted in the Paratill® as opposed to the control treatments (F=5.71; df=3,179; P=0.0010). There were more soil pores in the Paratilled compared with the B.C. Sub-mulched and control treatments in the AB layer (F=4.94; df=3,179; P=0.0027). There was no significant difference in the B layer.

Table 9 summarizes the comparison of pocket penetrometer readings in the topsoil, compact, and subsoil layers for each subsoiling treatment for each field (excluding field #11 due to insufficient data in 1989) between the years 1989 and 1990. For nine fields, there was indicated greater compaction of the soil in 1990 than 1989. In field numbers 4, 6, 9, 12 and 14, compaction appeared to be greater in 1989 in both the compact and subsoil layers.

Table 10 summarizes the findings of similar comparisons using bulk density data. According to these findings, overall, there was an insignificant difference between the years 1989 and 1990. Field numbers 4, 5, and 13 had some significant differences in bulk density readings in both the AB and B layers, however, no observable pattern (ie. either greater compaction in 1990 or 1989) was obvious.

3.7 EFFECTS OF SUBSOILING TREATMENTS ON YIELDS

Mean soybean and corn yields are presented in Figure 11 for 1990. For Sites 2 and 3 there were no available yield data, Site 7 was planted to tomatoes in 1990, and Site 13 provided overall yield data (no individual plot yields). There were four soybean fields (#1, 4, 6 and 9) and six corn fields (#5, 8, 10, 11, 12 and 14) used in the analysis. Comparisons between subsoiling treatments using overall means of both crops revealed that for corn, F= 1.51; df=3,41; P=0.2463, and soybeans, F=0.79; df=3,23; P=0.5344 (see Figure 11 for corn and soybean n values), there were no significant differences in yields due to the influence of subsoiling implements. Means of corn yields for individual sites ranged from 124 to 158 bu/ac. The Kent County 1990 average and five year average (1984-89) was 123 and 132 bu/ac, respectively. Since the test plots outperformed the County average for 1990 and in most cases were greater than the five year average, it appeared that stress was minimal on the co-operators' corn crops this year.

Means of soybean yields for individual sites ranged from 22 to 46 bu/ac. The county soybean results were 42 bu/ac for 1990 and 38 bu/ac for the five year average. The cool wet spring caused early emergence problems for a few co-operators growing soybeans (Sites 1, 4 and 13). Table 11 shows Sites 1 and 4 with the lowest soybean yields and both also had the most excess surface water. This poor drainage could be due partly to the tillage methods

Table 9. Comparison of Pocket Penetrometer Resistance Readings (kg/cm²) at Each Soil Layer Between the Years 1989 and 1990 for Each Subsoiling Treatment for Each Field.

FIELD NO.	SOIL LAYER	YEAR	TREATMENTS			
			STROHM A.	B.C. SUB.	CONTROL	PARATILL*
1	Compact	1989	---	---	2.56b*	1.94b
		1990	---	---	3.17a	2.58a
	Subsoil	1989	---	---	2.54b	1.63b
		1990	---	---	3.25a	2.35a
2	Topsoil	1989	1.27a	1.19b	1.50a	1.06b
		1990	1.52a	1.92a	1.58a	1.75a
	Compact	1989	2.33b	1.94b	2.85a	2.13b
		1990	3.54a	3.25a	3.25a	3.02a
	Subsoil	1989	2.29a	2.00a	2.33a	2.04b
		1990	2.46a	2.08a	2.56a	2.58a
3	Topsoil	1989	0.65b	0.85b	1.00a	---
		1990	1.38a	1.35a	1.15a	---
	Compact	1989	1.56b	2.06b	2.25b	---
		1990	3.00a	2.79a	3.25a	---
	Subsoil	1989	1.60b	1.71b	2.21a	---
		1990	2.67a	2.85a	2.69a	---
4	Compact	1989	2.42a	2.88a	2.85a	1.83a
		1990	2.44a	2.40b	2.44b	1.96a
	Subsoil	1989	2.42a	2.79a	2.52a	1.79a
		1990	2.27a	2.38b	2.50a	2.13a
5	Compact	1989	2.50b	2.73a	2.73a	---
		1990	2.92a	2.69a	2.77a	---
	Subsoil	1989	2.42a	2.60a	2.60a	---
		1990	2.50a	2.75a	2.42a	---
6	Compact	1989	1.23a	2.44a	2.85a	---
		1990	2.48a	2.48a	2.27b	---
	Subsoil	1989	2.17b	2.21a	2.60a	---
		1990	2.40a	2.35a	1.81b	---

*Note = For each soil layer in each field, values followed by the same letter in each column are not significantly different (DMRT, $\underline{P}$=0.05; n=2).

Table 9. Comparison of Pocket Penetrometer Resistance Readings (kg/cm²) at Each Soil Layer Between the Years 1989 and 1990 for Each Subsoiling Treatment for Each Field (concluded).

FIELD NO.	SOIL LAYER	YEAR	TREATMENTS			
			STROHM A.	B.C. SUB.	CONTROL	PARATILL®
7	Compact	1989	2.35a	2.67a	2.75b	2.35b
		1990	2.40a	2.60a	3.13a	2.73a
	Subsoil	1989	2.15b	2.31b	2.50a	2.23a
		1990	2.79a	2.65a	2.60a	2.38a
8	Compact	1989	2.19b	2.10b	2.81a	---
		1990	2.85a	2.67a	2.94a	---
	Subsoil	1989	2.04a	2.46a	2.65a	---
		1990	2.52a	2.40a	2.75a	---
9	Compact	1989	2.48a	2.67a	3.25a	---
		1990	2.71a	2.31b	2.50b	---
	Subsoil	1989	2.65a	2.56a	2.69a	---
		1990	2.10b	1.83b	2.15b	---
10	Topsoil	1989	1.21b	1.29a	1.54b	---
		1990	2.10a	1.75a	1.90a	---
	Compact	1989	1.88b	1.96b	2.19a	---
		1990	2.81a	2.54a	2.65a	---
	Subsoil	1989	2.52a	2.10b	2.42a	---
		1990	2.69a	2.63a	2.48a	---
12	Compact	1989	2.27a	2.92a	2.50a	2.79a
		1990	2.42a	2.58a	3.23a	1.85b
	Subsoil	1989	2.71a	2.67a	2.55a	2.58a
		1990	2.35a	2.50a	2.15b	2.17b
13	Compact	1989	2.27b	2.77a	2.67a	2.23a
		1990	2.56a	2.77a	2.60a	2.31a
	Subsoil	1989	2.08b	2.65a	2.42a	1.92a
		1990	2.33a	2.90a	2.25a	2.10a
14	Compact	1989	2.50a	2.58a	2.85a	2.63a
		1990	2.19a	2.06b	2.40b	2.21a
	Subsoil	1989	2.27a	2.23a	2.48a	2.40a
		1990	2.10a	2.13a	2.13b	2.13a

*Note = For each soil layer in each field, values followed by the same letter in each column are not significantly different (DMRT, $\underline{P}$=0.05; n=2).

Table 10. Comparison of Bulk Density Readings (g/cm³) in the AB and B Soil Layers for Each Subsoiling Treatment for Six Fields Between the Years 1989 and 1990.

FIELD NO.	SOIL LAYER	YEAR	STROHM A.	B.C. SUB.	CONTROL	PARATILL®
4	AB	1989	1.46a*	1.44a	1.42a	1.41a
		1990	1.41a	1.44a	1.52a	1.45a
	B	1989	1.49b	1.55a	1.45a	1.54a
		1990	1.54a	1.47b	1.49a	1.53a
5	AB	1989	1.54a	1.49a	1.43b	---
		1990	1.49a	1.55a	1.55a	---
	B	1989	1.63a	1.55a	1.56a	---
		1990	1.59a	1.58a	1.53a	---
7	AB	1989	1.43a	1.47a	1.47a	1.46a
		1990	1.47a	1.51a	1.41a	1.48a
	B	1989	1.47a	1.46a	1.43a	1.55a
		1990	1.52a	1.48a	1.39a	1.43a
12	AB	1989	1.56a	1.54a	1.70a	1.61a
		1990	1.59a	1.44a	1.62a	1.62a
	B	1989	1.61a	1.56a	1.77a	1.59a
		1990	1.66a	1.55a	1.61a	1.64a
13	AB	1989	1.54a	1.50a	1.70a	1.70a
		1990	1.54a	1.62a	1.50a	1.63a
	B	1989	1.55a	1.53b	1.70a	1.67a
		1990	1.61a	1.82a	1.57b	1.62b
14	AB	1989	1.38a	1.38a	1.39a	1.43a
		1990	1.41a	1.36a	1.36a	1.39a
	B	1989	1.48a	1.39a	1.53a	1.54a
		1990	1.55a	1.44a	1.44a	1.45a

*Note = For each soil layer in each field, values followed by the same letter in each column are not significantly different (DMRT, $\underline{P}$=0.05; n=2).

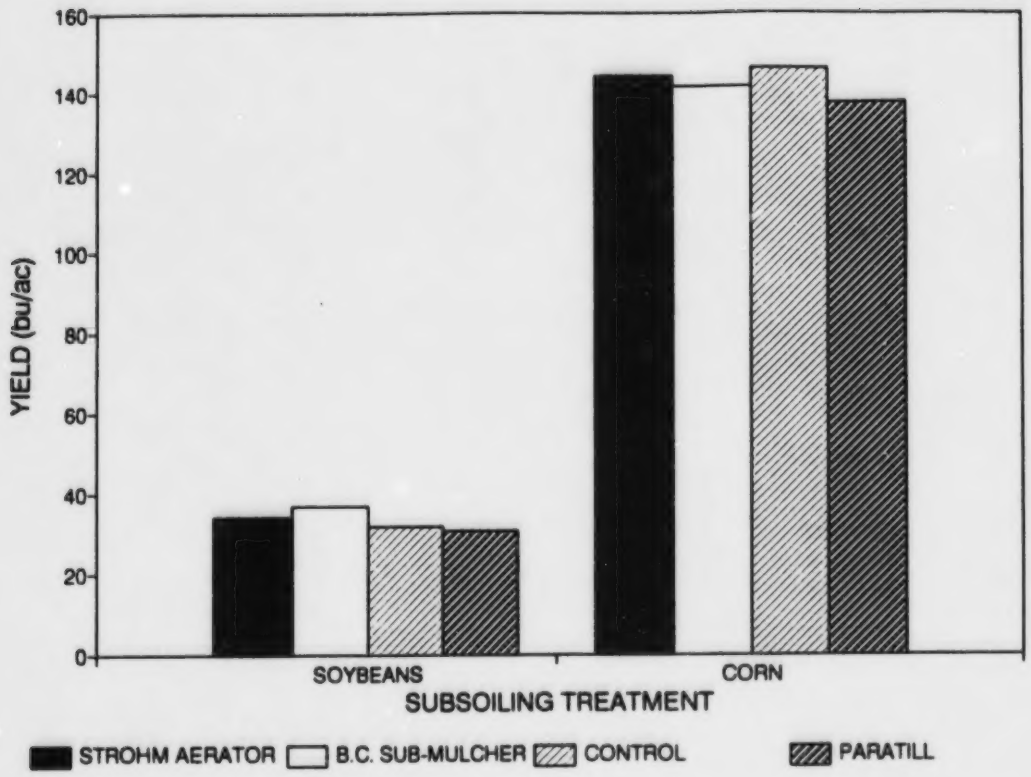


Figure 11. 1990 Soybean and Corn Yields One Year after Subsoiling with Different Implements. (For soybeans - Strohm aerator® and B.C Sub-mulcher®, n=6; Control n=8; Paratill® n=4: for corn - all subsoiling treatments n=12, except Paratill® n=6).

(Site 1 - chisel, Site 4 - no till) or soil conditions. In both of these sites the Paratill® produced considerable better yields, possibly due to the better drainage associated with this implement. The moldboard plowed soybeans had better overall yields which could be the result of better moisture infiltration combined with better aeration.

3.8 YIELD VERSUS MANAGEMENT PRACTICES AND SOIL CHARACTERISTICS

Table 11 compares yields to key management factors including type of tillage, fertilization, previous crops grown, and clover plowdown. This table shows that ridge till produced the greatest corn yields. Paired t-tests were conducted on plots that were not plowed deeply (eliminating site numbers 6, 9, 11, and 14) from the analysis. No significant differences were found in yield response. Site 8 was in soybeans the previous year and therefore received virtually no tillage, whereas at the other ridge till sites, clover was plowed under in the fall. The next two highest yielding corn fields received the greatest addition of nitrogen in the spring.

As mentioned in the previous section, a couple of the soybean sites had excess surface water that hindered crop yields. The conservation tillage practices could be one factor for the 1990 poor results at these sites since the plowed sites provided considerably better yields.

Table 11 also compares yield to various soil parameters. Soil texture appeared to play an important role for the 1990 results as almost all the silty clay sites produced the best yields. An overall compaction rating was also included in this table which was based on the guidelines table for quantifying compaction indicators (Appendix A - Table 15).

Suggested links between management practices and soil characteristics to yields are tentative explanations since greater numbers of sites are needed to provide a better idea of crop responses.

3.9 1990 PEARSON CORRELATION ANALYSES

The PCM which correlated soil fertility and yield variables for control treatments for 1990 (Table 12) revealed some interesting findings. Corn yields were positively correlated with greater nitrogen additions (r=0.62; n-2=20; P=0.0019). Soybean yields correlated positively with both nitrogen and phosphorous fertilizer additions. Soybean yields also increased with greater levels of phosphorous (r=0.42; n-2=22; P=0.04) and calcium in the soil.

Organic matter in the topsoil increased as organic matter content (r=0.54; n-2=26; P=0.003) and pH in the AB layer (r=0.41; n-2=26; P=0.03) of the soil increased. It was negatively associated with both potassium and magnesium in the AB layer. Greater organic matter in the AB layer correlated with greater calcium (r=0.55; n-2=26; P=0.002) and less magnesium (r=-0.38; n-2=26; P=0.045) in the soil.

Table 11. 1990 Mean Crop Yields, Type of Tillage, Fertilization, Previous Crop (1989), and Soil Characteristics (Texture, Topsoil Depth, and Organic Matter) for Each Site.

Site	Corn Yield (bu/ac)				Soybean Yield (bu/ac)				Tillage System	Fertilization (kg/ha)			Previous Crop (1989)	Texture		Topsoil Depth* (cm)	Organic Matter (%)		Compaction Rating
	S.A.**	B.C.	Con.	Par.	S.A.	B.C.	Con.	Par.		N	P	K		A	AB		A	AB	
1	-	-	-	-	-	-	18.5	25.5	conservation	0	0	0	winter wheat	SiCL	SiCL	17	3.7	3.4	moderate
2	-	-	-	-	-	-	-	-	conservation	-	-	-	beets	SL	SL	16	18.1	5.5	moderate
3	-	-	-	-	-	-	-	-	conservation	-	-	-	tomatoes	SL	SL	15	5.6	5.0	moderate-severe
4	-	-	-	-	19.6	27.2	25.7	35.6	no till	0	0	0	winter wheat	SiC***	SiC	12	5.5	4.9	moderate
5	127.6	128.3	135.8	-	-	-	-	-	shallow plow	104	31	31	winter wheat	SiC***	SiC	15	4.7	4.3	moderate
6	-	-	-	-	45.9	46.3	45.6	-	deep plow	0	0	0	winter wheat	SiC	SiC	15	4.3	4.2	moderate
7	-	-	-	-	-	-	-	-	ridge till	103	90	134	winter wheat	C***	SiC	17	4.2	3.7	moderate
8	168.4	150.6	154.1	-	-	-	-	-	ridge till	162	67	67	soybeans	SiC	SiC	12	4.9	4.2	slight-moderate
9	-	-	-	-	36.9	36.6	37.5	-	deep plow	0	168	140	seed corn	CL	CL	15	4.3	4.1	moderate
10	152.6	150.3	149.3	-	-	-	-	-	shallow plow	233	146	112	winter wheat	SiC	SiC	15	4.5	3.8	moderate
11	155.0	154.3	153.9	151.6	-	-	-	-	deep plow	233	146	112	winter wheat	SiC	SiC	16	4.1	3.6	moderate
12	124.0	124.5	127.0	121.0	-	-	-	-	ridge till	210	90	45	winter wheat	CL***	CL	17	3.9	2.9	moderate
13	-	-	-	-	-	42.0	-	-	shallow plow	0	0	0	winter wheat	CL***	CL	16	4.0	4.3	moderate
14	136.5	141.0	141.0	140.0	-	-	-	-	deep plow	206	83	34	winter wheat	SiC***	SiC	14	6.8	6.7	severe-moderate

* Topsoil is depth of humus enriched soil, including A and part of AB layer.
** Treatment codes are as follows; S.A. = Strohm aerator®, B.C. = B.C. Sub-mulcher®, Con. = Control, Par. = Paratill®.
*** Particle size analysis on these samples, the rest were hand textured.

For yield values, n=2. Yields for Sites 2,3 = no available data; Site 7 = tomatoes; Site 13 = overall yield.
All winter wheat was underseeded with clover.

Table 12. 1990 Pearson Correlation Matrix (Soil Fertility and Yields)

	YR CORN	YR SOY	OM A	OM AB	N ADD	P ADD	K ADD	P FeA	P FeAB	K FeA	K FeAB	Mg FeA	Mg FeAB	Ca FeA	Ca FeAB	pH A	pH AB
YRCORN																	
YRSOY																	
OMA																	
OMAB			+														
NADD	+	+															
PADD		+			+												
KADD					+	+											
PFeA						+	+										
PFeAB		+				+	+	+									
KFeA								+	+								
KFeAB			-				+		+	+							
MgFeA								+	+	+	+						
MgFeAB			-	-							+	+					
CaFeA		+		+		+	+	+	+	+							
CaFeAB				+		+	+	+	+					+			
pHA								+			-		-	+	+		
pHAB			+		+	+	+	+			-		-	+	+	+	

Not surprisingly, fertilizer additions (nitrogen, phosphorous and potassium) were positively correlated with each other and with fertility levels in the soil. Soil reaction (pH) decreased as potassium and magnesium levels increased in the AB soil layer. It was, however, positively correlated with calcium levels (r=0.61; n-2=26; P=0.000; AB layer) in the soil.

The PCM which correlated soil physical properties, estimated loading, and yields for control treatments in 1990 (Table 13) also revealed important findings. Dickey-john® penetrometer readings were generally positively correlated with pocket penetrometer readings. Dickey-john® and pocket penetrometer readings were negatively correlated with sand content of the soil (soil texture analyzed in 1989). Bulk density values were positively correlated with pocket penetrometer readings, and they matched with the farmers' assessment of compaction (FACA). Bulk density values increased as levels of soil organic matter decreased in the A layer (r=-0.92; n-2=18; P=0.000) and the AB layer (r=-0.72; n-2=18; P=0.0003). There was a positive correlation between sand content and bulk density values. Also, a negative correlation between silt and clay content of the soil and bulk density values was shown.

Organic matter in the topsoil increased as earthworm abundance and number and size of pores increased in the AB layer (r=0.50; n-2=26; P=0.006). Greater number of passes and greater cumulative loading correlated negatively with levels of organic matter content in the soil. Abundance of earthworms and soil pores were positively correlated with each other. However, both parameters decreased as soil compaction ratings increased (eg. WAB versus CR, r=-0.72; n-2=26; P=0.000). Figure 12 is a scattergram which has the soil pore ratings (P) plotted against the compaction ratings (CR) for control treatments for each site in 1990. The general slope of the points show that as compaction ratings increased in the AB or compact layer (approx. 15-25 cm depth), pore abundance and size is reduced (r=-0.85; n-2=26; P=0.000).

Corn yields were positively correlated with abundance of earthworms in the B layer (r=0.55; n-2=20; P=0.006). Soybean yields, however, were negatively correlated with abundance of worms, and decreased with increasing FACA (r=-0.76; n-2=22; P=0.000). There was a positive correlation between soybean yields and clay content in the topsoil (r=0.60; n-2=10; P=0.039).

The number of passes, cumulative loading, and FACA (farmers assessment of compaction on his land) parameters were also analyzed to observe if any correlation exists between them. It was observed that as the number of passes (r=0.97; n-2=22; P=0.000) and estimates of cumulative loading increased (r=0.41; n-2=22; P=0.04) so did the FACA.

Table 13. 1990 Pearson Correlation Matrix (Soil Physical Properties, Loading and Yields)

	DJ 3	DJ 4	DJ 5	DJ 6	PO A	PO AB	PO B	BD A	BD AB	BD B	W A	W AB	W B	P A	P AB	P B	CR	YR CORN	YR SOY	FA CA	PA SS	OM A	OM AB	CUM WF	SA A	SA AB	SA B	Si A	Si AB	Si B	CL A	CL AB	CL B
DJ3																																	
DJ4	+																																
DJ5		+																															
DJ6			+																														
POA	+	+																															
POAB	+	+																															
POB	+	+				+																											
BDA				+																													
BDAB				+				+																									
BDB					−			+	+																								
WA																																	
WAB				−				−																									
WB												+																					
PA											+																						
PAB												+																					
PB												+	+		+																		
CR												−	−		−	−																	
YRCORN													+																				
YRSOY		−										−																					
FACA					+		+	+		+									−													38
PASS						+																											
OMA				−				−	−	−		+			+						−												
OMAB								−	−	−											−	+											
CUMWF																				+	+		−										
SAA					−			+	+	+										+		−	−										
SAAB			−		−			+	+	+										+		−	−		+								
SAB			−		−			+	+	+										+	+	−	−		+	+							
SiA																				+	−	+	+				−						
SiAB			+					−	−	−										+		+	+		−	−	−	+					
SiB								−	−	−					−					+		+	+		−	−	−	+	+				
CLA	−											−	−			−	+		+	+				+									
CLAB					+			−	−	−										+		+	+		−	−	−		+	+			
CLB																									−	−	−	+	+	+	+		

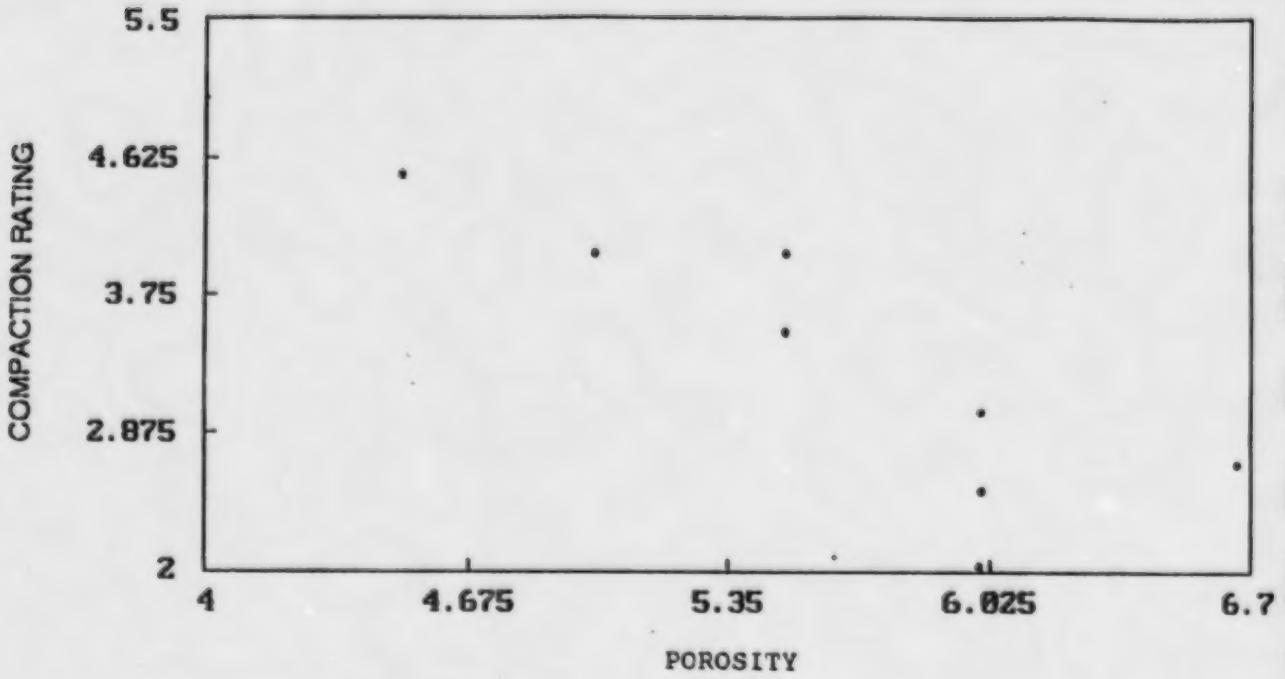


Figure 12. Compaction (CR) versus Soil Pore (P) Ratings for Control Treatments in the AB Layer for Fourteen Sites in 1990.

Pearson correlation analysis of soil physical properties and other parameters with visual compaction ratings revealed few correlations for the year 1990. In the first year of this study (1989) and the previous Can-Ag compaction study (1988) there were many correlations between visual compaction ratings and certain soil parameters, in particular, penetrometer resistance and bulk density. The same Can-Ag personnel conducted all three of these soil compaction rating investigations therefore inconsistencies due to human observation should be minimal.

The most likely reason for 1990's paucity of correlations was the excessive amount of moisture in the soil at the time of investigation (November 1990). Another reason could have been the statistical analysis: almost all sites were assigned an overall moderately compacted rating for compaction therefore any statistical significance would have been difficult to detect.

Figures 13 to 16 show mean values for Dickey-john®, pocket penetrometer, bulk density readings and compaction ratings, respectively, for control treatments in the AB or compact layer of soils over all sites for 1989 and 1990. In general, soil compaction increased slightly from 1989 to 1990. Dickey-john® penetrometer readings had an overall significant increase from 1989 (267.5 lbs/in^2) to 1990 (305 lbs/in^2) (t=2.82; df=47; P=0.0098; n=24). Pocket penetrometer reading means were 2.66 kg/cm^2 in 1989, increasing to 2.75 kg/cm^2 in 1990 (t=0.69; df=51; P=0.4936; n=26), and bulk density measurements were 1.48 g/cm^3 in 1989 and 1.51 g/cm^3 in 1990 (t=1.07; df=53; P=0.2940; n=27), however, these increases were not statistically significant. Compaction ratings increased from 1989 (3.22) to 1990 (3.34) but this change was not significant (t=1.05; df=51; P=0.3013; n=26).

3.10 CONDITIONS AFFECTING IMPLEMENT DRAUGHT

Table 14 compares the draughts of each implement (at the four sites) with the soil conditions found at those sites. The recording of data for the computerized tractor took place in a 30 metre section within the treatment. The reported draught is the average of three passes within that section, which was adjusted for implement width and depth. Therefore, the draught requirement between treatments and sites was compared.

The number of shanks per subsoiler varied with each implement: B.C. Sub-mulcher® had 5 shanks (76 cm spacing - 305 cm total width); Strohm aerator® had 3 shanks (76 cm spacing - 152 cm total width); and the Paratill® had 4 shanks (66 cm spacing on ends, 109 cm spacing in middle - 241 cm total width). At Site 7 only two shanks were used on the Paratill®.

There was a noticeable difference in draught requirements between Site 14 and the other three sites even though all but Site 12 had similar soil textures. Site 14 had the lowest draught of all sites, but there were only a couple parameters that differed between locations.

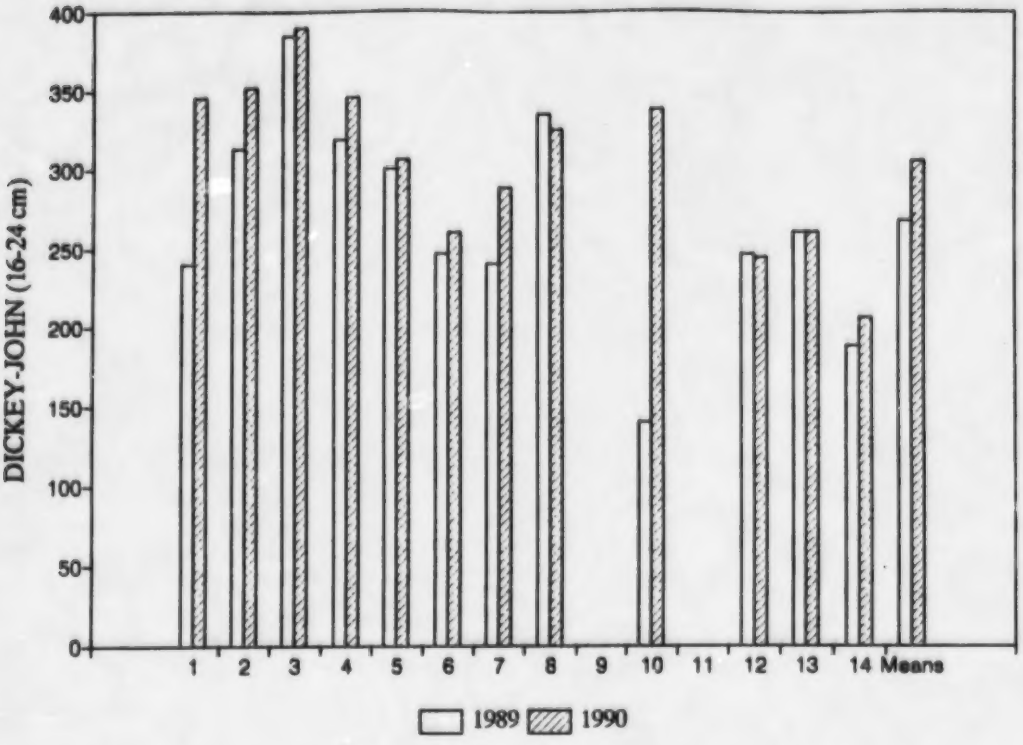


Figure 13. Comparison of Mean Dickey-john® Penetrometer Readings for 1989 and 1990 for Each Site.

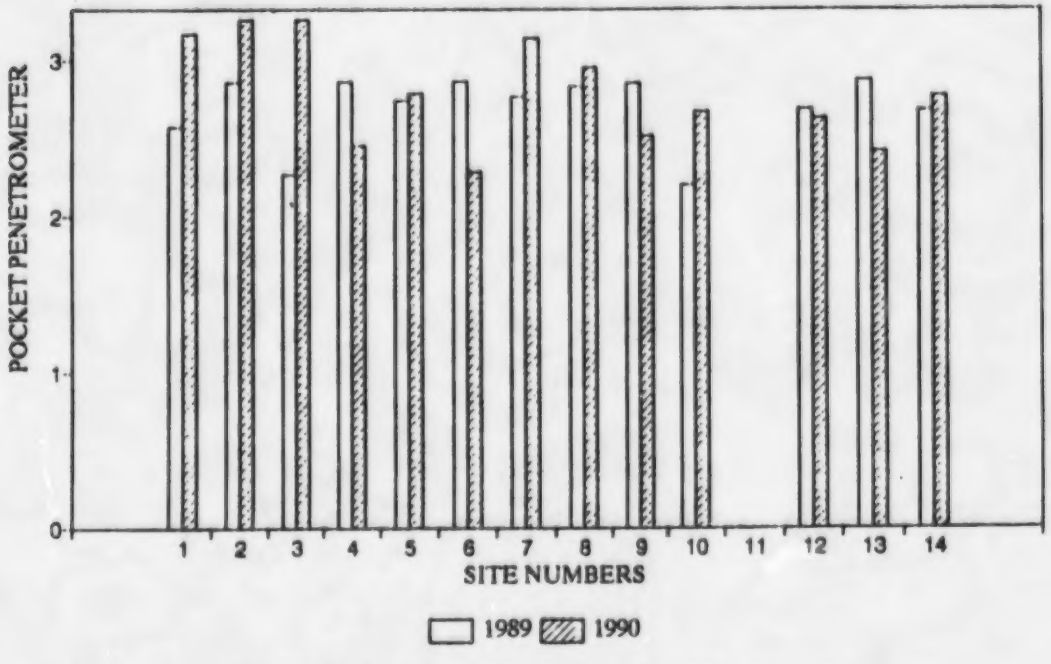


Figure 14. Comparison of Mean Pocket Penetrometer Readings for 1989 and 1990 for Each Site.

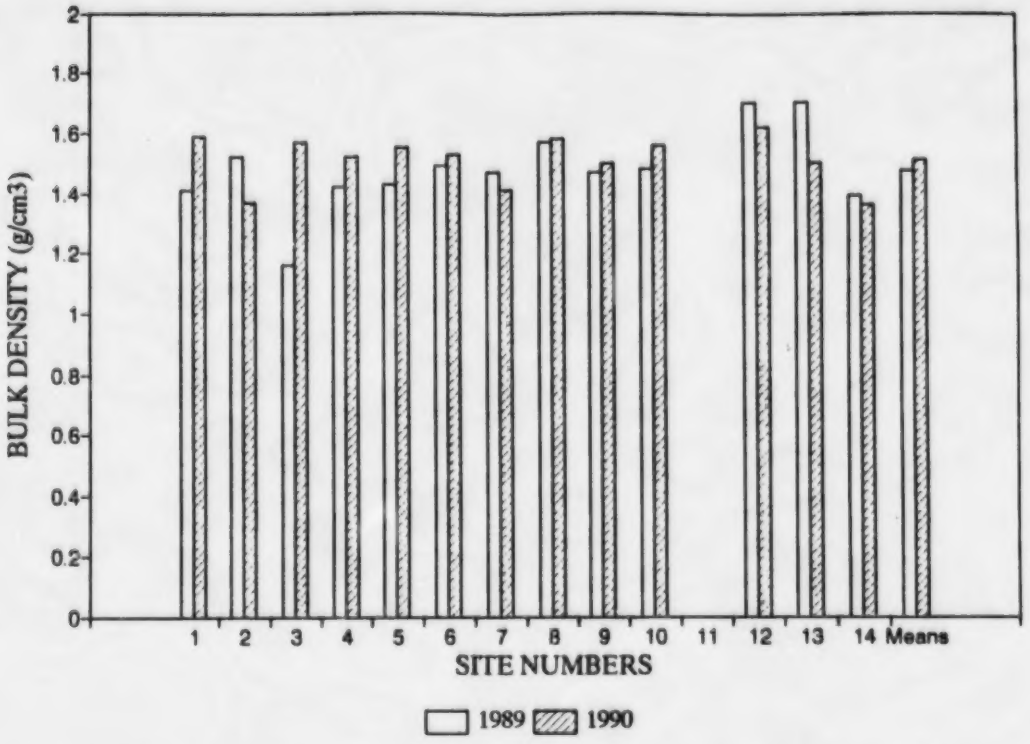


Figure 15. Comparison of Mean Bulk Density Readings for 1989 and 1990 for Each Site.

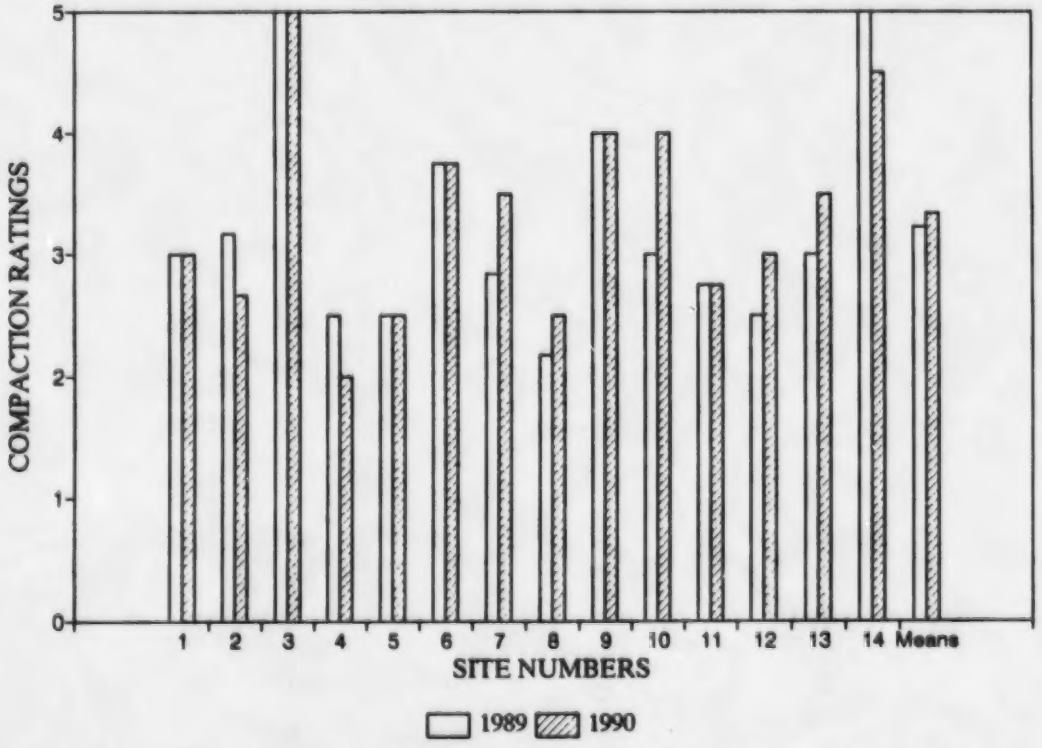


Figure 16. Comparison of Mean Compaction Ratings for 1989 and 1990 for Each Site.

Table 14. 1989 Implement Draught Calculations and Related Soil Parameters for Sites 7, 11, 12 and 14.

Site	Rep	Implement Draught (Newtons) B.C.*	Strohm	Par.	DJ (6-32cm)	B.D. (g/cm³)	O.M. (%) A	AB	CR	% Soil Moisture (15-30cm)	Texture A	AB	Under-seeded to Clover
7	1	83,392	117,441	92,186 (2 shanks)	267	1.47	4.2	3.7	3	26	C	SiC	yes
	2	74,215	98,979	72,630 (2 shanks)	248				3	26			
11	1	43,504	71,195	80,766	-	1.54	4.1	3.6	3	22	SiC	SiC	yes
	2	43,649	68,396	90,870	-				2	24			
12	1	57,972	78,024	84,101	267	1.70	3.9	2.9	2	23	CL	CL	yes
	2	53,166	83,282	113,576	247				3	24			
14	1	38,575	31,118	45,562	189	1.39	6.8	6.7	5	30	SiC	SiC	yes
	2	31,250	40,163	52,630	207				5	33			

* Treatment codes are as follows: B.C. = B.C. Sub-mulcher®, Strohm = Strohm aerator®, Par. = Paratill®.
Note: See Appendix C for explanation of parameter codes.

Gravimetric soil moisture content was highest at Site 14 which could have contributed to lower soil resistance, but would have hindered the subsoiler's soil shattering abilities. The other parameter was organic matter which was considerably higher at Site 14 and thus improved the soil tilth and lowered the soil resistance. Table 14 indicated that the penetrometer resistance corresponds fairly well to the required draught. Since only a few sites provided draught information, caution is advised in linking draught to soil conditions.

3.11 1989 TRACTOR PERFORMANCE WITH DIFFERENT SUBSOILERS

Raw data were obtained from Agriculture Canada's Computerized Tractor indicating draught and fuel use required to pull the different subsoilers, then corrected for the different widths of the three implements. On site 11 (M. Parry), fuel consumption was significantly greatest when subsoiling with the Strohm aerator® (27.1 L/ha) when compared with the Paratill® (22.2 L/ha) (t=3.84; df=22; P=0.0008), or with the B.C. Sub-mulcher® (11.7 L/ha) (t=14.34; df=21; P=0.000). The B.C. Sub-mulcher® implement required significantly less fuel when compared with the Paratill® (t=10.85; df=21; P=0.000). The draught in Newtons (N) required to pull the implements was greatest with the Paratill® (85,818 N) when compared with the Strohm aerator® (69,795 N) (t=3.80; df=22; P=0.0009) or the B.C. Sub-mulcher® (43,583 N) (t=9.87; df=21; P=0.000). The draught required to pull the Strohm aerator® was significantly greater when compared with that of the B.C. Sub-mulcher® (t=6.32; df=21; P=0.000) (Figure 17).

On site 12 (Skipper), Figure 18 shows that fuel use was significantly increased with the Strohm aerator® (33.1 L/ha) compared with the Paratill® (27.8 L/ha) (t=2.56; df=17; P=0.02), or with the B.C. Sub-mulcher® (13.1 L/ha) (t=16.9; df=18; P=0.000). The use of the Paratill® resulted in more fuel consumption compared with that of the B.C. Sub-mulcher® (t=9.15; df=19; P=0.000). The B.C. Sub-mulcher® required the least draught (55,362 N) compared with the Strohm aerator® (80,361 N) (t=4.64; df=18; P=0.0002) or compared with the Paratill® (101,786 N) (t=7.05; df=19; P=0.000). The Paratill® required significantly more draught when compared with the Strohm aerator® (t=3.27; df=17; P=0.004).

For site 14 (Wonnacott), use of the Strohm aerator® required the most fuel (25.6 L/ha) compared with the Paratill® (21.3 L/ha) (t=8.71; df=14; P=0.000) and the B.C. Sub-mulcher® (16.0 L/ha) (t=13.8; df=15; P=0.000). The Paratill® required significantly more fuel compared with the B.C. Sub-mulcher® (t=7.09; df=13; P=0.000) (Figure 18). The Paratill® implement required the greatest draught (48,591 N) compared with the Strohm aerator® (37,148 N) (t=4.04; df=14; P=0.001) or the B.C. Sub-mulcher® (35,828 N) (t=3.28; df=13; P=0.006).

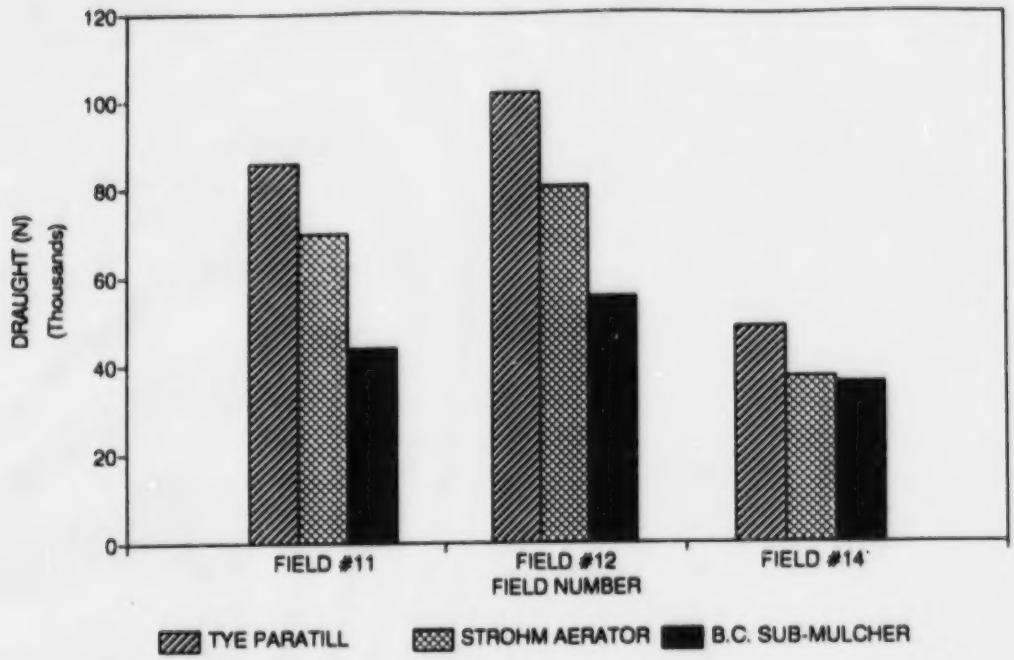


Figure 17. Draught in Newtons (N) needed to pull three subsoiling implements in several fields (M. Parry, Skipper, and Wonnacott).

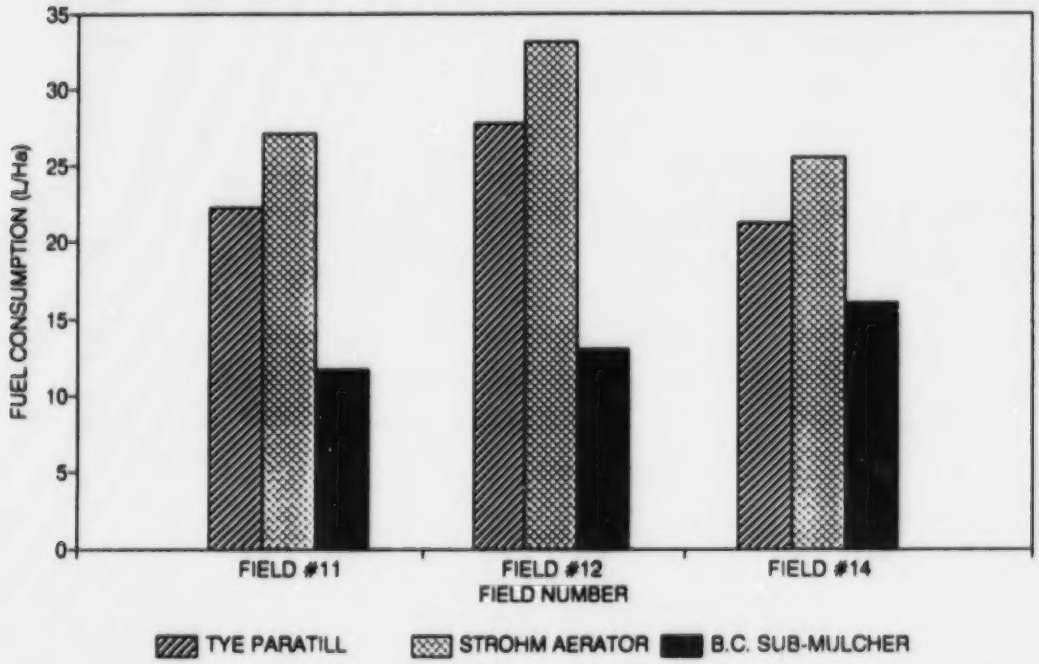


Figure 18. Fuel consumption (L/ha) used in pulling three subsoiling implements in several fields (M. Parry, Skipper, and Wonnacott).

There was no significant difference between the Strohm aerator® and B.C. Sub-mulcher® with respect to draught (t=0.40; df=15; P=0.6979) (Figure 17).

On both sites 11 and 12, there were no significant measurable differences in fuel use or in draught required between passes. There were no measurable differences between passes in fuel consumption on site 14, however, the Strohm aerator® implement required the most draught in Pass 2 compared with the Paratill® (t=0.67; df=15; P=0.514) or the B.C. Sub-mulcher® (t=3.09; df=11; P=0.01).

For sites 11 and 12 draught was significantly positively correlated with fuel use; site 11 (r=0.76; n-2=33; P=0.000) and site 12 (r=0.72; n-2=28; P=0.000). Figure 19 is a scattergram which shows the overall linear relation of draught in Newtons (N) versus fuel consumption for site 11. In site 11 fuel use was positively correlated with the draught required to pull the Strohm aerator® (r=0.94; n-2=10; P=0.000), the Paratill® (r=0.91; n-2=10; P=0.000), and the B.C. Sub-mulcher® (r=0.61; n-2=9; P=0.048). For Site 12 fuel use was significantly positively correlated with draught for the Paratill® implement (r=0.92; n-2=8; P=0.0001) and the B.C. Sub-mulcher® (r= 0.85; n-2=9; P=0.0009). For Site 14, one correlation was found to exist with the B.C. Sub-mulcher® with respect to fuel use and draught required (r=0.84; n-2=6; P=0.008).

With each implement the draught was significantly positively correlated with fuel use. However, when comparisons were done between implements, the Paratill® required the greatest draught and the Strohm aerator® required the greatest amount of fuel. This result was not positively correlated and was therefore suspect. This problem was discussed with Dr. J. Culley, one of the research scientists involved with the computerized tractor, and he questioned the accuracy of the draught measurements as well for problems with recording this variable had occurred in later trials.

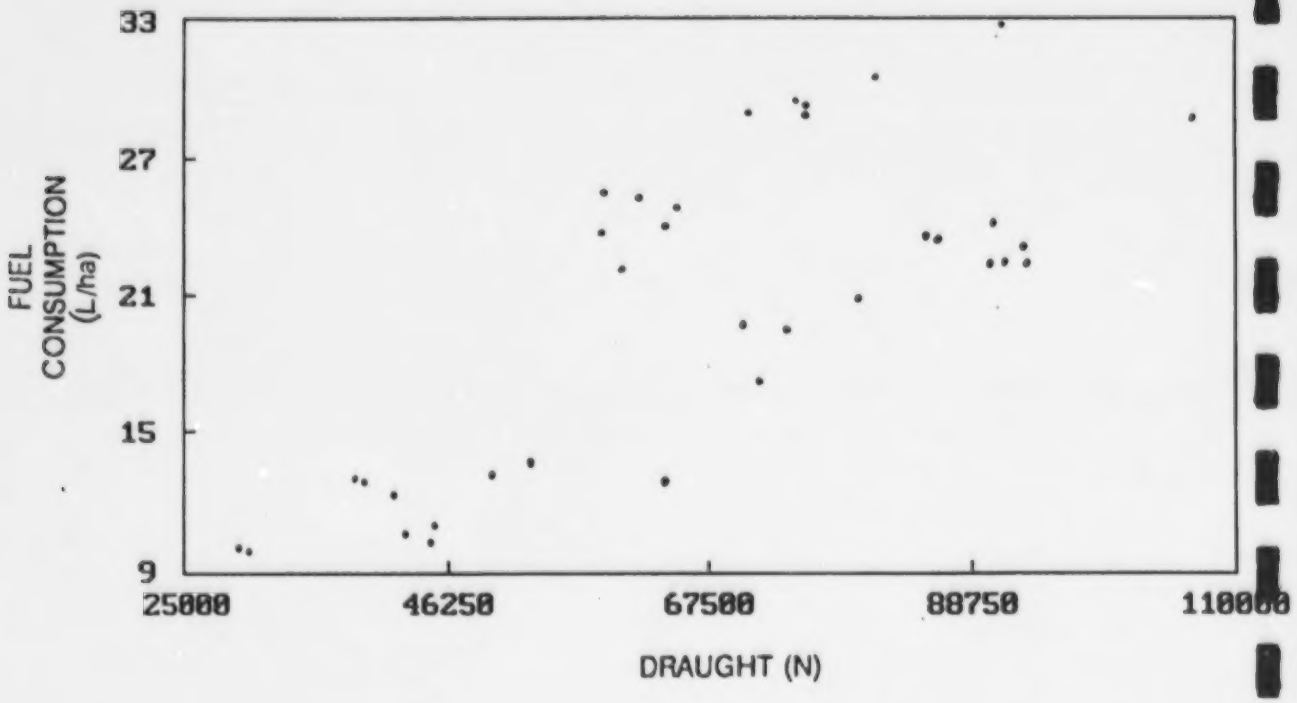


Figure 19. Site 11 - Draught in Newtons (N) versus Fuel Use (L/ha) in 1989.

4.0 SUMMARY

Earlier research by Can-Ag Enterprises (1988) indicated that in southwestern Ontario about 42% of clay and clay loam soils were moderately compacted below the plow layer (15-20 cm) and an additional 16% were severely compacted. Impacts on yields were estimated to be about 12% and 25% reductions, respectively, based on literature and farmers estimates. Factors contributing to subsoil compaction include heavy tractors, increased number of passes, high soil moisture content during operations, and choice of crops. Compaction correlated with crops grown in this order: forages < small grasses < row crops < silage corn and tomatoes. This effect arises from a combination of timing of operations with respect to moisture content, number of operations, and axle loads of equipment used. Generally, there are fewer earthworms in compacted soils.

Studies reported in the literature indicate that natural amelioration of subsoil compaction through freeze-thaw and wetting-drying cycles is a very slow process, too slow to be practical in a farming operation. Subsoiling is considered to be one method to alleviate the problem, however, its effectiveness and duration are questionable. It is known that for successful subsoiling, soils should be dry enough to permit shattering of the soil.

Another study was undertaken during the 1988 growing season by Can-Ag Enterprises (1989) working together with the Southwestern Ontario Agricultural Research Corporation (S.W.O.A.R.C.). In this project, field length strips in corn fields were subsoiled in late June to determine whether shallow (18 cm) and deep (31 cm) subsoiling with a B.C. Sub-mulcher® would be beneficial. This was a very dry season and crops were poor due to drought. Shallow subsoiling was detrimental, presumably because soils tended to dry out more. Deep subsoiling was helpful, although yield comparisons in either treatment were not statistically significantly different from the control plots (no subsoiling). Most of the soils were rated as being moderately compacted, however, on two severely compacted fields the deep subsoiling increased yield about 10% above the control plots. There were not enough plots on severely compacted soils to measure statistical differences; nevertheless, the trend appeared to be promising. Subsequently, a third subsoiling study was undertaken and it is summarized next.

Field length strips were subsoiled in the fall using different implements (Strohm aerator®, B.C. Sub-mulcher®, and Paratill®) at the 25-35 cm depth on fourteen farms, after soybean or winter wheat harvest in 1989. Corn or soybeans were grown in 1990 using normal farming practices employed by the co-operating farmers. Soil conditions, crop response and yields were carefully monitored in 1990 to evaluate the performance of the different implements in comparison to control plots. Soil observations and measurements of compaction were made

after subsoiling in 1989 and repeated after harvest in 1990 to determine the impact of the various implements on soil structure and compaction.

Visual examination of soils indicated that twelve of the fields were slightly to moderately compacted while only two were moderately to severely compacted. Measurement of bulk density in the AB layer (about 15 - 25 cm depth interval) indicated that, in 1989, eight control sites had densities exceeding 1.45 g/cm^3. Note, however, that two of these are sandy and higher densities are expected. According to the 1988 Can-Ag study, values greater than 1.45 g/cm^3 are considered to be moderately severely compacted for clay loam to clay soils. Calibration of visual observations is difficult. Based on visual examination of soils and ratings thus assigned, a good crop response to subsoiling might only have been expected on a couple of sites. Based on measurements of bulk density, using 1.45 g/cm^3 in the AB layer as the threshold value, positive crop responses to subsoiling might have as been expected on about half the farms.

In comparison to the 30 year average, the 1990 growing season was drier and cooler in spring, near average in summer, and wetter with near average temperature in fall. Corn yields were below the past five year average, and soybeans were above the average for Kent County.

Crop response in 1990 to subsoiling in fall of 1989 was minimal on most fields, in fact, there was no significant difference in yields among treatments across all farms. Soybean yields on four farms ranged from 18.5 to 46.3 bu/ac including all treatments. There was a good response to the Paratill® treatment (7 to 10 bu/ac increase) on two low yielding soybean fields but this was not statistically significant because too few sites responded so favourably. Mean corn yields on six farms ranged from 121.0 to 168.4 bu/ac. Yield differences between farms were quite large, usually as much as 30 bu/ac for matched treatments. On any given farm, there was less than 5 bu/ac difference among the subsoiling treatments. Therefore, 1990 yields suggest that subsoiling was ineffective.

Soil conditions observed and measured in 1989 and 1990 indicated significant differences among treatments. The Paratill® was clearly the most effective implement in reducing soil compaction. Residual effects of subsoiling one year later were evident in the Paratilled plots but not those subsoiled with the B.C. Sub-mulcher® or the Strohm aerator®. Fuel consumption was significantly greatest with the Strohm aerator®, followed by the Paratill®, then the B.C. Sub-mulcher®. Therefore, the Paratill® provides the best subsoiling results considering both soil response and fuel expenditures. Yet the cost of subsoiling is approximately $35 per hectare including subsoiler rental and fuel consumption (not including tractor depreciation and labour) and since no increased yields resulted from the operation, it

was not an economic benefit. Under different climatic conditions an increased yield might be obtained through subsoiling and therefore the operations benefits might outweigh the costs.

Some farmers plow deep (about 30 cm). This appears to be as effective as subsoiling in ameliorating the annual compaction caused by farming operations as well as improving water infiltration. It seems that below this depth, the inherent subsoil structure is strong enough to withstand the loadings and has not deteriorated to date.

5.0 RECOMMENDATIONS

Potentially limiting subsoil compaction is confined to the interval ranging more or less, from 15 to 25 cm. Therefore, tillage practices such as deep plowing or chiselling should alleviate compaction at this depth. It is the authors' opinion that subsoiling may only be warranted on severely compacted soils. Farmers are not likely to get a significant crop response to subsoiling moderately or slightly compacted soils even though moderately compacted soils are estimated to reduce yields by about 12%.

Farmers should adopt other management practices which tend to alleviate soil compaction. These include:

- reduction in vehicle weights (axle loads),
- avoiding working on wet or very moist soils,
- limiting the number of passes over the field, especially if moist, and
- utilizing cropping systems and rotations which facilitate the above and provide crops with deep rooting action as well as maintain or improve soil organic matter content.

On severely compacted soils subsoiling may be viable, however, farmers should establish trials first to determine whether there is a significant and economical yield response. Adoption of the above mentioned practices is also advised to reduce re-compaction of the soils likely to occur in one or two years.

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7.0 APPENDICES

7.1 APPENDIX A

1989 Input Data (Penetrometer Readings, Bulk Densities, Worm, Pore, Compaction and Subsoiler Ratings, Soil Fertility, Particle Size Analysis, Past Yield and Management Factors, Fertilizer Additions, and Percent Soil Moisture at Time of Subsoiling).

Table 15. Guidelines for Quantifying Compaction Indicators for Soils Examined.

Compaction Indicator	DEGREE OF COMPACTION		
	SLIGHT	MODERATE	SEVERE
Profile Compaction Rating (CR)	1 2 None Slight	3 4 Slight-Moderate Moderate	5 6 Moderate-Severe Severe
Bulk Density (BD) AB (g/cm^3)	<1.30	(1.37)*	>1.45
Dickey-john Penetrometer Index	<240	240 - 300 (270)	>300
Pocket Penetrometer Index	<2.1	2.45 2.1 - 2.8	>2.8
Pore Rating (P) AB	>7.0	(5.5) 7.0 - 4.0	<4.0

* Mean value overall.
<1.30 class numerical values (mean plus and minus two standard deviations)

Table 16. 1989 Penetrometer Readings.

SITE NO.	TRT*	REP	DICKEY-JOHN® (Mean of 6 Readings)						POCKET (Mean of 6 Readings)		
			1 (0-8 cm)	2 (8-16 cm)	3 (16-24 cm)	4 (24-32 cm)	5 (32-40 cm)	6 (40-48 cm)	A	AB	B
1	3	1	66.67	145.83	212.50	279.17	387.50	400.00		2.50	2.54
		2	129.17	195.83	266.67	320.83	383.33	400.00		2.63	2.54
	4	1	58.33	100.00	158.33	212.50	266.67	329.17		1.75	1.54
		2	108.33	166.67	191.67	254.17	737.83	387.50		2.13	1.71
2	1	1	95.83	158.33	208.33	258.33	287.50	308.33	1.58	2.38	2.33
		2	108.33	195.83	262.50	308.33	316.67	329.17	0.96	2.29	2.25
	2	1	87.50	166.67	241.67	270.83	295.83	337.50	1.17	1.75	1.88
		2	83.33	170.83	245.83	279.17	295.83	304.17	1.21	2.13	2.13
	3	1	191.67	229.17	350.00	366.67	379.17	400.00	2.00	3.00	2.46
		2	129.17	212.50	275.00	304.17	341.67	370.83	1.00	2.71	2.21
	4	1	125.00	187.50	229.17	279.17	312.50	329.17	1.08	2.00	1.96
		2	58.33	120.83	183.33	245.83	279.17	295.83	1.04	2.25	2.13
3	1	1	104.17	179.17	279.17	283.33	304.17	362.50	0.67	1.83	1.79
		2	100.00	150.00	229.17	300.00	375.00	358.33	0.63	1.29	1.42
	2	1	108.33	191.67	266.67	295.83	345.83	387.50	0.96	2.50	2.00
		2	112.50	179.17	229.17	283.33	345.83	370.83	0.75	1.63	1.42
	3	1	116.67	250.00	391.67	354.17	395.83	400.00	1.08	2.13	1.75
		2	129.17	258.33	379.17	379.17	400.00	383.33	0.92	2.38	2.67
4	1	1		233.33	341.67	366.67	391.67	400.00		2.58	2.67
		2	141.67	183.33	241.67	300.00	337.50	366.67		2.25	2.17
	2	1		241.67	341.67	391.67	400.00	400.00		3.04	2.92
		2	125.00	191.67	245.83	270.83	337.50	391.67	1.50	2.71	2.67
	3	1		266.67	358.33	400.00	400.00	400.00		3.04	2.83
		2	175.00	212.50	279.17	337.50	391.67	400.00		2.67	2.21
	4	1		158.33	216.67	316.67	375.00	400.00		2.21	1.92
		2	62.50	120.83	158.33	237.50	300.00	391.67	1.17	1.46	1.67

* Treatments are 1= Strohm aerator®, 2= B.C. Sub-mulcher®, 3= Control, and 4= Paratill®. Missing values = no available data.

Table 16. 1989 Penetrometer Readings (Continued).

SITE NO.	TRT*	REP	DICKEY-JOHN® (Mean of 6 Readings)						POCKET (Mean of 6 Readings)		
			1 (0-8 cm)	2 (8-16 cm)	3 (16-24 cm)	4 (24-32 cm)	5 (32-40 cm)	6 (40-48 cm)	A	AB	B
5	1	1		216.67	291.67	350.00	400.00	400.00		2.67	2.67
		2		166.67	266.67	308.33	375.00	400.00		2.33	2.17
	2	1		208.33	266.67	366.67	400.00	400.00		3.00	2.79
		2		183.33	275.00	333.33	400.00	400.00		2.46	2.42
	3	1		200.00	283.33	358.33	383.33	400.00		2.50	2.46
		2		216.67	316.67	375.00	400.00	400.00		2.96	2.75
6	1	1		158.33	241.67	283.33	341.67	400.00		2.25	2.17
		2		166.67	208.33	283.33	350.00	391.67		2.21	2.17
	2	1		225.00	291.67	341.67	383.33	400.00		2.33	2.21
		2		191.67	241.67	341.67	383.33	400.00		2.54	2.21
	3	1		183.33	250.00	308.33	383.33	400.00		2.83	2.63
		2		158.33	241.67	325.00	375.00	400.00		2.88	2.58
7	1	1	125.00	162.50	229.17	295.83	354.17	375.00		2.79	2.50
		2	104.17	137.50	175.00	237.50	329.17	358.33		1.92	1.79
	2	1	141.67	200.00	241.67	320.83	362.50	391.67		2.79	2.46
		2	141.67	166.67	216.67	270.83	345.83	358.33		2.54	2.17
	3	1	129.17	204.17	254.17	341.67	387.50	400.00		2.96	2.75
		2	162.50	195.83	225.00	320.83	358.33	395.83		2.54	2.25
	4	1	116.67	175.00	220.83	283.33	345.83	391.67		2.54	2.50
		2	150.00	183.33	225.00	295.83	325.00	350.00		2.17	1.96
8	1	1	179.17	212.50	283.33	333.33	370.83	400.00	2.33	2.42	2.63
		2	175.00	212.50	258.33	316.67	358.33	379.17	1.58	1.96	1.46
	2	1	166.67	191.67	250.00	312.50	362.50	391.67		2.46	2.71
		2	141.67	187.50	254.17	291.67	341.67	354.17	1.63	1.75	2.21
	3	1	241.67	295.83	362.50	391.67	400.00	400.00		3.13	2.96
		2	195.83	245.83	308.33	362.50	391.67	400.00	2.00	2.50	2.33

* Treatments are 1= Strohm aerator®, 2= B.C. Sub-mulcher®, 3= Control, and 4= Paratill®. Missing values = no available data.

Table 16. 1989 Penetrometer Readings (Continued).

SITE NO.	TRT*	REP	DICKEY-JOHN® (Mean of 6 Readings)						POCKET (Mean of 6 Readings)		
			1 (0-8 cm)	2 (8-16 cm)	3 (16-24 cm)	4 (24-32 cm)	5 (32-40 cm)	6 (40-48 cm)	A	AB	B
9	1	1	112.50	133.33	183.33	308.33	366.67	395.83		2.50	2.58
		2	100.00	141.67	150.00	241.67	308.33	375.00		2.46	2.71
	2	1	79.17	104.17	241.67	300.00	370.83	400.00		2.33	2.38
		2	108.33	154.17	154.17	233.33	329.17	370.83		3.00	2.75
	3	1	83.33	116.67	187.50	275.00	341.67	387.50			2.42
		2	120.83	175.00	212.50	283.33	345.83	387.50		3.25	2.96
10	1	1	50.00	50.00	100.00	229.17	300.00	350.00	1.21	1.33	1.88
		2	54.17	66.67	104.17	212.50	291.67	295.83		2.42	3.17
	2	1	50.00	100.00	154.17	308.33	383.33	400.00	1.29	1.96	2.17
		2	66.67	75.00	145.83	254.17	295.83	345.83			2.04
	3	1	58.33	66.67	100.00	254.17	312.50	375.00	1.54	1.79	2.17
		2	62.50	95.83	179.17	258.33	312.50	329.17		2.58	2.67
11	1	1									
		2									
	2	1									
		2									
	3	1									
		2									
	4	1									
		2									

* Treatments are 1= Strohm aerator®, 2= B.C. Sub-mulcher®, 3= Control, and 4= Paratill®. Missing values = no available data.

Table 16. 1989 Penetrometer Readings (Concluded).

SITE NO.	TRT*	REP	DICKEY-JOHN® (Mean of 6 Readings)						POCKET (Mean of 6 Readings)		
			1 (0-8 cm)	2 (8-16 cm)	3 (16-24 cm)	4 (24-32 cm)	5 (32-40 cm)	6 (40-48 cm)	A	AB	B
12	1	1		200.00	225.00	283.33	366.67	400.00		2.38	2.63
		2		208.33	300.00	375.00	391.67	400.00		2.17	2.79
	2	1		233.33	275.00	325.00	391.67	400.00		2.96	2.75
		2		183.33	258.33	305.00	391.67	400.00		2.88	2.58
	3	1		250.00	241.67	308.33	366.67	400.00		2.00	2.33
		2		166.67	250.00	325.00	366.67	400.00		2.58	2.33
	4	1		233.33	283.33	375.00	391.67	400.00		3.33	2.88
		2		183.33	216.67	308.33	391.67	391.67		2.25	2.29
13	1	1		166.67	266.67	333.33	375.00	391.67		2.33	2.29
		2	25.00	154.17	245.83	295.83	333.33	362.50		2.21	1.88
	2	1		158.33	200.00	300.00	358.33	391.67		3.21	2.92
		2		133.33	229.17	308.33	379.17	391.67		2.33	2.38
	3	1		150.00	250.00	316.67	383.33	400.00		2.75	2.50
		2	50.00	166.67	270.83	320.83	375.00	400.00		2.58	2.33
	4	1		200.00	275.00	300.00	350.00	383.33		2.33	2.25
		2		166.67	233.33	316.67	375.00	391.67		2.13	1.58
14	1	1	137.50	150.00	158.33	254.17	337.50	387.50		2.54	2.29
		2	112.50	137.50	175.00	279.17	337.50	391.67		2.46	2.25
	2	1	83.33	100.00	154.17	220.83	316.67	375.00		2.58	2.17
		2	120.83	150.00	187.50	241.67	325.00	391.67		2.58	2.29
	3	1	108.33	120.83	170.83	275.00	337.50	395.83		2.63	2.25
		2	95.83	125.00	204.17	291.67	370.83	400.00		3.08	2.71
	4	1	100.00	120.83	166.67	258.33	312.50	358.33		2.38	2.46
		2	87.50	116.67	145.83	258.33	300.00	358.33		2.88	2.33

* Treatments are 1= Strohm aerator®, 2= B.C. Sub-mulcher®, 3= Control, and 4= Paratill®. Missing values = no available data.

Table 17. 1989 Bulk Densities.

SITE NO.	TRT*	REP	BULK DENSITIES (g/cm³)					
			Ax	Ay	ABx	ABy	Bx	By
1	3	1			1.42	1.40	1.33	1.38
		2						
	4	1						
		2						
2	1	1						
		2						
	2	1						
		2						
	3	1	1.26	1.42	1.51	1.53	1.68	1.65
		2						
	4	1						
		2						
3	1	1						
		2						
	2	1						
		2						
	3	1	1.07	1.04	0.98	1.33	1.41	1.55
		2						
4	1	1			1.42	1.39	1.49	1.48
		2						
	2	1			1.44	1.43	1.55	1.54
		2						
	3	1			1.39	1.44	1.46	1.44
		2						
	4	1			1.37	1.44	1.55	1.50
		2						
5	1	1			1.59	1.48	1.65	1.61
		2						
	2	1			1.49	1.49	1.54	1.56
		2						
	3	1			1.41	1.44	1.58	1.53
		2						

* Treatments are 1= Strohm aerator®, 2= B.C. Sub-mulcher®, 3= Control, and 4= Paratill®.
Missing values = no available data.

Table 17. 1989 Bulk Densities (Continued).

SITE NO.	TRT*	REP	BULK DENSITIES (g/cm³)					
			Ax	Ay	ABx	ABy	Bx	By
6	1	1						
		2						
	2	1						
		2						
	3	1			1.47	1.50	1.56	1.52
		2						
7	1	1			1.45	1.41	1.41	1.52
		2						
	2	1			1.49	1.45	1.45	1.47
		2						
	3	1			1.49	1.45	1.40	1.46
		2						
	4	1			1.46	1.45	1.48	1.62
		2						
8	1	1						
		2						
	2	1						
		2						
	3	1	1.28	1.35	1.59	1.55	1.56	1.68
		2						
9	1	1						
		2						
	2	1						
		2						
	3	1			1.43	1.51	1.47	1.49
		2						
10	1	1						
		2						
	2	1						
		2						
	3	1			1.34	1.61	1.41	1.58
		2						

* Treatments are 1= Strohm aerator®, 2= B.C. Sub-mulcher®, 3= Control, and 4= Paratill®.
Missing values = no available data.

Table 17. 1989 Bulk Densities (Concluded).

SITE NO.	TRT*	REP	BULK DENSITIES (g/cm³)					
			Ax	Ay	ABx	ABy	Bx	By
11	1	1						
		2						
	2	1						
		2						
	3	1	0.86		1.54		1.25	
		2						
	4	1						
		2						
12	1	1			1.55	1.56	1.65	1.57
		2						
	2	1			1.53	1.54	1.51	1.61
		2						
	3	1			1.68	1.72	1.81	1.73
		2						
	4	1			1.59	1.62	1.61	1.57
		2						
13	1	1			1.50	1.58	1.54	1.55
		2						
	2	1			1.53	1.46	1.54	1.52
		2						
	3	1			1.65	1.75	1.70	1.70
		2						
	4	1			1.68	1.71	1.67	1.67
		2						
14	1	1			1.42	1.33	1.51	1.44
		2						
	2	1			1.40	1.35	1.47	1.30
		2						
	3	1			1.33	1.44	1.50	1.55
		2						
	4	1			1.44	1.42	1.55	1.52
		2						

* Treatments are 1= Strohm aerator®, 2= B.C. Sub-mulcher®, 3= Control, and 4= Paratill®.
Missing values = no available data.

Table 18. 1989 Worm, Pore, Compaction and Subsoiler Ratings.

SITE NO.	TRT*	REP	WORMS			PORES			CR	SR
			A**	AB	B	A	AB	B		
1	3	1	2	1	2	7	6	7	3	
		2	2	1	2	7	4	7	3	
	4	1	2	1	1	7	4	8	3	2
		2	3	2	2	7	6	8	3	2
2	1	1	3	3	3	8	7	8	2	3
		2	3	3	3	8	7	7	3	2
	2	1	2	3	2	7	7	7	2	1
		2	2	2	3	8	8	8	2	2
	3	1	2	2	3	7	5	7	4	
		2	2	3	3	8	8	8	1	
	4	1	3	3	3	8	7	7	2	4
		2	3	4	4	7	8	8	1	4
3	1	1	3	2	2	8	4	6	5	2
		2	2	2	2	8	5	6	4	3
	2	1	2	1	2	8	3	5	5	1
		2	2	1	2	8	3	4	5	1
	3	1	2	1	1	7	3	4	5	
		2	2	2	2	8	3	6	5	
4	1	1	2	2	2	8	6	6	3	1
		2	2	2	2	8	6	8	2	1
	2	1	2	2	2	8	6	6	3	1
		2	2	2	2	8	6	6	2	1
	3	1	2	2	2	8	6	6	3	
		2	2	3	3	8	7	8	2	
	4	1	2	2	2	8	6	6	3	2
		2	2	2	2	8	6	6	3	2
5	1	1	2	2	2	8	6	6	3	2
		2	2	2	3	8	7	8	2	1
	2	1	2	2	2	8	6	7	3	1
		2	2	2	2	8	6	8	3	1
	3	1	2	2	2	8	6	8	3	
		2	2	2	3	8	6	8	2	

* Treatments are 1= Strohm aerator®, 2= B.C. Sub-mulcher®, 3= Control, and 4= Paratill®.
** A, AB and B represent soil layers.
CR = compaction rating, SR = subsoiling rating. Missing values = no available data.

Table 18. 1989 Worm, Pore, Compaction and Subsoiler Ratings (Continued).

SITE NO.	TRT*	REP	WORMS			PORES			CR	SR
			A**	AB	B	A	AB	B		
6	1	1	2	2	2	8	6	8	3	2
		2	3	2	2	8	6	8	3	2
	2	1	2	2	2	8	6	8	3	1
		2	2	2	2	8	6	8	3	1
	3	1	2	2	3	8	4	8	4	
		2	2	2	2	8	4	8	4	
7	1	1	4	3	2	8	6	7	2	1
		2	3	3	4	8	8	8	2	1
	2	1	2	2	2	8	6	8	3	1
		2	2	2	2	8	6	8	3	1
	3	1	2	2	3	8	6	8	3	
		2	2	2	2	8	6	8	3	
	4	1	4	3	3	8	8	8	2	2
		2	2	2	3	8	6	8	3	2
8	1	1	4	4	3	8	8	8	2	2
		2	2	2	2	8	6	8	3	2
	2	1	4	4	4	8	8	8	2	1
		2	3	3	3	8	8	8	2	1
	3	1	4	3	3	8	8	8	2	
		2	4	2	2	8	6	8	3	
9	1	1	2	2	2	8	6	7	3	1
		2	2	2	3	8	5	8	4	1
	2	1	2	2	2	8	5	7	4	1
		2	2	2	2	8	4	8	4	1
	3	1	2	2	2	8	5	8	4	
		2	2	2	2	8	5	8	4	
10	1	1	2	2	2	8	6	8	3	1
		2	2	2	2	8	8	8	2	1
	2	1	2	2	2	8	5	7	3	1
		2	2	2	2	8	6	8	3	1
	3	1	2	2	2	8	5	7	3	
		2	2	2	2	8	6	7	3	

* Treatments are 1= Strohm aerator®, 2= B.C. Sub-mulcher®, 3= Control, and 4= Paratill®.
** A, AB and B represent soil layers.
CR = compaction rating, SR = subsoiling rating. Missing values = no available data.

Table 18. 1989 Worm, Pore, Compaction and Subsoiler Ratings (Concluded).

SITE NO.	TRT*	REP	WORMS			PORES			CR	SR
			A**	AB	B	A	AB	B		
11	1	1	2	3	2	8	7	8	2	1
		2	2	2	2	8	6	8	3	1
	2	1	2	2	2	8	6	7	3	1
		2	2	3	3	8	6	8	2	1
	3	1	2	2	2	8	6	8	3	
		2	2	3	3	8	6	8	2	
	4	1	2	3	3	8	7	8	2	2
		2	2	3	3	8	8	8	2	2
12	1	1	2	2	3	8	6	8	3	2
		2	2	2	2	8	6	7	3	2
	2	1	2	3	2	8	7	8	2	1
		2	2	2	2	8	6	7	3	1
	3	1	2	3	3	8	8	8	2	
		2	2	2	2	8	6	8	3	
	4	1	2	2	2	8	7	8	2	2
		2	2	2	2	8	6	8	3	2
13	1	1	2	3	3	8	6	8	2	1
		2	2	2	2	8	7	8	2	1
	2	1	2	3	2	8	6	8	3	1
		2	2	2	2	8	7	8	2	1
	3	1	2	2	2	8	5	8	3	
		2	2	2	2	8	6	7	3	
	4	1	2	2	2	8	6	8	3	2
		2	2	3	3	8	7	7	2	2
14	1	1	3	2	3	8	4	7	4	2
		2	2	2	2	8	4	6	4	2
	2	1	3	2	2	8	3	7	5	1
		2	2	2	3	8	4	8	4	1
	3	1	2	2	3	8	3	7	5	
		2	2	2	2	8	4	7	5	
	4	1	2	2	2	8	3	7	5	3
		2	2	3	3	8	6	8	4	3

* Treatments are 1= Strohm aerator®, 2= B.C. Sub-mulcher®, 3= Control, and 4= Paratill®.
** A, AB and B represent soil layers.
CR = compaction rating, SR = subsoiling rating. Missing values = no available data.

Table 19. 1989 Soil Fertility Results.

SITE NO.	OM%		FERTILITY (ppm)														
			P			K			Mg			Ca			pH		
	A	AB	A	AB	B	A	AB	B	A	AB	B	A	AB	B	A	AB	B
1	4.2	4.1	38	29	4	390	262	232	863	762	787	4540	3995	4385	6.2	6.4	6.7
2	5.2	5.2	39	19	3	215	128	71	375	421	394	5400	6563	3938	7.2	7.3	7.6
3	10.1	6.2	35	4	2	113	52	41	551	315	234	4366	3877	4236	7.2	7.2	7.4
4	5.1	4.7	9	5	3	179	154	125	324	318	317	4410	5050	4121	6.6	6.4	6.6
5	4.4	3.4	28	17	15	247	175	152	456	510	519	3479	3638	3466	5.9	6.1	6.6
6	4.1	3.9	22	12	3	215	227	164	586	920	645	4309	3770	3937	6.4	6.5	6.7
7	4.2	3.5	56	21	4	304	174	104	747	792	790	5341	5640	5622	6.4	6.9	7.0
8	4.1	3.4	43	22	3	234	199	126	530	611	501	3742	4454	3889	6.8	6.7	6.9
9	4.4	4.4	54	39	4	320	168	414	580	600	640	4660	6114	6331	5.8	6.3	6.9
10	4.2	3.9	68	45	12	246	254	246	644	670	545	5556	2847	5657	6.4	6.4	6.8
11	4.2	4.1	27	17	4	303	186	211	520	505	195	3030	3720	2841	6.1	6.4	6.7
12	3.7		22	12	3	191	114	253	440	531	820	1869	2296	1869	5.7	5.9	6.1
12a	3.7		12	3	2	117	54	62	170	117	159	3340	1579	1204	6.2	6.4	6.5
13			14	7	3	206	197	190	387	481	535	3043	3326	3199	6.2	6.2	6.5
14			42	35	4	306	210	186	605	687	732	4809	5410	5297	5.7	5.9	6.3

Missing values = no available data.

Table 20. 1989 Particle Size Analysis.

SITE NO.	% SAND			% SILT			% CLAY		
	A	AB	B	A	AB	B	A	AB	B
1									
2									
3									
4	12.3	12.1	11.3	42.8	43.8	44.0	6.6	44.2	44.8
5	17.5	16.2	15.9	41.5	41.7	40.4	41.0	42.1	43.7
6									
7	14.6	6.7		38.7	42.3		46.7	51.0	
8									
9									
10									
11									
12	32.4	33.3	35.5	40.1	38.8	31.8	27.6	27.9	32.7
12a	52.0	43.9	67.2	32.2	41.4	22.7	15.9	14.8	10.1
13	22.7	21.0	15.7	43.4	42.5	42.4	33.8	36.5	41.9
14	3.5	3.4	3.3	45.9	44.0	51.9	50.6	52.6	44.7

Missing values = no available data.

Table 21. 1989 Past Yield and Management Factors.

SITE NO.	YR CORN	YR SOY	FACA	TT COV.	PASS	CUM Wt/Ft.	T1 HP	T2 HP	T3 HP
1	113		3	122	3	3570	140	130	75
2									
3									
4		40	2	115	3	2480	110	50	
5	130	43	2	195	3	4060	160	90	65
6	129	41	2	248	6	6100	140	80	65
7	190	38	2	146	5	3590	160	130	85
8	168	50	2	91	4	3160	140	125	120
9	27	47	2	351	8	7640	145	65	45
10	155	54	2	140	3	4190	160	100	80
11	27	52	2	140	3	4190	160	100	80
12	170	47	2	239	4	4590	130	125	
12a	170	47	2	239	4	4590	130	125	
13	110	45	2	215	4	4500	170	150	80
14	164	52	2	151	3	3360	170	120	70

Note: See Appendix C for explanation of parameter codes.
Missing values = no available data.

Table 22. 1989 Management Factors: Fertilizer Additions (kg/ha).

SITE	N ADD	P ADD	K ADD
1	135	69	0
2			
3			
4	91	0	0
5	54	97	32
6	92	63	31
7	103	140	140
8	0	0	0
9	210	135	58
10	62	0	0
11	62	0	0
12	124	47	24
12a	124	47	24
13	100	65	40
14	127	72	36

Note: See Appendix C for explanation of parameter codes.
Missing values = no available data.

Table 23. 1989 Soil Moisture (%) at Time of Subsoiling.

SITE NO.	REP NO.	DEPTH (cm)	% MOISTURE* (gravimetric)
1	1	0-15 15-30	
2	1	0-15 15-30	27.4 26.7
3	1	0-15 15-30	40.8 32.8
4	1	0-15 15-30	22.8 21.6
5	1	0-15 15-30	
6	1	0-15 15-30	
7	1 2	0-15 15-30 0-15 15-30	27.0 26.4 26.9 25.7
8	1	0-15 15-30	28.8 28.2
9	1	0-15 15-30	19.0 24.6
10	1	0-15 15-30	21.5 20.4
11	1 2	0-15 15-30 0-15 15-30	24.8 22.0 21.8 24.2

* These sites were subsoiled by the farmers, therefore soil samples were not obtained on the day of the operation.

Table 23. 1989 Soil Moisture (%) at Time of Subsoiling (Concluded).

SITE NO.	REP NO.	DEPTH (cm)	% MOISTURE (gravimetric)
12	1	0-15	23.9
		15-30	23.2
	2	0-15	25.4
		15-30	23.8
13	1	0-15	28.0
		15-30	26.2
	2	0-15	26.0
		15-30	20.8
14	1	0-15	29.2
		15-30	30.1
	2	0-15	36.7
		15-30	33.2

7.2 APPENDIX B

1990 Input Data (Penetrometer Readings, Bulk Densities, Worm, Pore, Compaction and Subsoiler Ratings, Soil Fertility, Past Yield and Management Factors, and Fertilizer Additions).

Table 24. 1990 Penetrometer Readings.

SITE NO.	TRT*	REP	DICKEY-JOHN® (Mean of 6 Readings)						POCKET (Mean of 6 Readings)		
			1 (0-8 cm)	2 (8-16 cm)	3 (16-24 cm)	4 (24-32 cm)	5 (32-40 cm)	6 (40-48 cm)	A	AB	B
1	3	1	241.67	295.83	333.33	400.00	400.00	400.00		3.08	3.63
		2	170.83	262.50	358.33	387.50	400.00	400.00		3.25	2.88
	4	1	179.17	262.50	287.50	345.83	400.00	400.00		2.54	2.46
		2	208.33	283.33	362.50	400.00	400.00	400.00		2.63	2.25
2	1	1	204.17	329.17	370.83	395.83	400.00	400.00	1.54	3.75	2.71
		2	195.83	295.83	337.50	375.00	391.67	400.00	1.50	3.33	2.21
	2	1	220.83	291.67	358.33	383.33	400.00	400.00	2.13	3.33	2.00
		2	204.17	279.17	345.83	379.17	387.50	395.83	1.71	3.17	2.17
	3	1	220.83	308.33	341.67	379.17	400.00	400.00	1.46	3.54	2.83
		2	208.33	275.00	362.50	383.33	383.33	383.33	1.71	2.96	2.29
	4	1	220.83	325.00	370.83	395.83	400.00	400.00	1.79	2.54	3.00
		2	200.00	258.33	320.83	358.33	387.50	395.83	1.71	3.50	2.17
3	1	1	200.00	350.00	400.00	400.00	400.00	400.00	1.33	3.00	2.75
		2	158.33	245.83	370.83	395.83	400.00	400.00	1.42	3.00	2.58
	2	1	204.17	312.50	387.57	400.00	400.00	400.00	1.71	2.71	2.96
		2	183.33	308.33	391.67	400.00	400.00	400.00	1.00	2.88	2.75
	3	1	204.17	304.17	379.17	400.00	400.00	400.00	1.04	3.00	2.17
		2	233.33	358.33	400.00	400.00	400.00	400.00	1.25	3.50	3.21
4	1	1	162.50	229.17	320.83	395.83	400.00	400.00	2.04	2.46	2.08
		2	175.00	233.33	308.33	379.17	400.00	400.00	1.83	2.42	2.46
	2	1	137.50	204.17	308.33	370.83	400.00	400.00	1.58	2.46	2.38
		2	175.00	262.50	329.17	400.00	400.00	400.00	2.17	2.33	2.38
	3	1	175.00	266.67	350.00	400.00	400.00	400.00	1.79	2.17	2.83
		2	158.33	258.33	341.67	400.00	400.00	400.00	1.92	2.71	2.17
	4	1	133.33	204.17	245.83	304.17	362.50	400.00	1.29	1.83	2.29
		2	183.33	229.17	262.50	316.67	379.17	400.00	2.71	2.08	1.96

* Treatments are 1= Strohm aerator®, 2= B.C. Sub-mulcher®, 3= Control, and 4= Paratill®. Missing values = no available data.

Table 24. 1990 Penetrometer Readings (Continued).

SITE NO.	TRT*	REP	DICKEY-JOHN® (Mean of 6 Readings)						POCKET (Mean of 6 Readings)		
			1 (0-8 cm)	2 (8-16 cm)	3 (16-24 cm)	4 (24-32 cm)	5 (32-40 cm)	6 (40-48 cm)	A	AB	B
5	1	1	162.50	250.00	316.67	383.33	400.00	400.00	1.63	2.54	2.42
		2	150.00	225.00	308.33	379.17	400.00	400.00	2.42	3.29	2.58
	2	1	175.00	250.00	308.33	375.00	400.00	400.00	1.54	2.63	2.88
		2	170.83	250.00	320.83	383.33	400.00	400.00	1.21	2.75	2.63
	3	1	170.83	233.33	312.50	379.17	400.00	400.00	1.88	2.79	2.58
		2	145.83	225.00	300.00	370.83	395.83	400.00	1.83	2.75	2.25
6	1	1	133.33	191.67	270.83	379.17	400.00	400.00	1.25	2.38	2.33
		2	154.17	191.67	270.83	350.00	400.00	400.00	1.54	2.58	2.46
	2	1	112.50	166.67	262.50	370.83	387.50	400.00	1.38	2.38	2.29
		2	141.67	183.33	254.17	354.17	400.00	400.00	1.46	2.58	2.42
	3	1	133.33	200.00	279.17	358.33	400.00	400.00	1.42	2.42	1.88
		2	133.33	166.67	241.67	333.33	400.00	400.00	1.46	2.13	1.75
7	1	1	133.33	229.17	329.17	387.50	400.00	400.00		2.42	2.75
		2	133.33	158.33	229.17	320.83	370.83	400.00		2.38	2.83
	2	1	170.83	237.50	320.83	383.33	400.00	400.00		2.63	2.88
		2	154.17	195.83	241.67	337.50	391.67	400.00		2.58	2.42
	3	1	166.67	225.00	295.83	370.83	400.00	400.00		2.92	2.71
		2	120.83	212.50	279.17	350.00	391.67	400.00		3.33	2.50
	4	1	129.17	179.17	237.50	291.67	341.67	375.00		2.54	2.17
		2	112.50	204.17	258.33	320.83	379.17	400.00		2.92	2.58
8	1	1	204.17	275.00	341.67	400.00	400.00	400.00	2.13	2.96	2.33
		2	191.67	245.83	312.50	362.50	400.00	400.00	1.58	2.75	2.71
	2	1	162.50	229.17	291.67	350.00	395.83	400.00	2.17	2.63	2.21
		2	175.00	250.00	304.17	370.83	400.00	400.00	1.50	2.71	2.58
	3	1	170.83	250.00	308.33	358.33	391.67	400.00	1.75	2.46	3.00
		2	187.50	279.17	341.67	387.50	400.00	400.00	1.96	3.42	2.50

* Treatments are 1= Strohm aerator®, 2= B.C. Sub-mulcher®, 3= Control, and 4= Paratill®. Missing values = no available data.

Table 24. 1990 Penetrometer Readings (Continued).

SITE NO.	TRT*	REP	DICKEY-JOHN® (Mean of 6 Readings)						POCKET (Mean of 6 Readings)		
			1 (0-8 cm)	2 (8-16 cm)	3 (16-24 cm)	4 (24-32 cm)	5 (32-40 cm)	6 (40-48 cm)	A	AB	B
9	1	1				266.67	333.33	370.83		2.71	2.46
		2				237.50	312.50	350.00			1.75
	2	1				295.83	341.67	391.67		2.29	1.92
		2				316.67	350.00	383.33		2.33	1.75
	3	1				316.67	383.33	400.00		2.21	2.00
		2				333.33	370.83	395.83		2.79	2.29
10	1	1	179.17	245.83	308.33	345.83	379.17	391.67	2.00	2.92	2.75
		2	175.00	216.67	312.50	391.67	400.00	400.00	2.21	2.71	2.63
	2	1	179.17	237.50	308.33	379.17	400.00	400.00	1.33	3.04	2.83
		2	175.00	220.83	295.83	383.33	400.00	400.00	2.17	2.04	2.42
	3	1	175.00	216.67	325.00	387.50	400.00	400.00	1.63	3.54	2.83
		2	237.50	304.17	350.00	395.83	400.00	400.00	2.17	1.75	2.13
11	1	1	154.17	154.17	241.67	320.83	370.83	387.50	1.42	3.21	2.67
		2	179.17	233.33	291.67	354.17	383.33	400.00	1.83	2.88	2.58
	2	1	158.33	187.50	291.67	362.50	379.17	400.00	1.21	2.71	2.38
		2	170.83	245.83	300.00	358.33	391.67	400.00	2.25	3.21	2.67
	3	1	195.83	241.67	325.00	345.83	391.67	400.00	2.25	3.50	3.13
		2	141.67	204.17	270.83	337.50	387.50	400.00	1.17	3.38	2.42
	4	1	145.83	191.67	229.17	337.50	387.50	400.00	1.42	3.38	2.83
		2	162.50	229.17	275.00	312.50	362.50	391.67	1.63	2.88	1.96

* Treatments are 1= Strohm aerator®, 2= B.C. Sub-mulcher®, 3= Control, and 4= Paratill®. Missing values = no available data.

Table 24. 1990 Penetrometer Readings (Concluded).

SITE NO.	TRT*	REP	DICKEY-JOHN® (Mean of 6 Readings)						POCKET (Mean of 6 Readings)		
			1 (0-8 cm)	2 (8-16 cm)	3 (16-24 cm)	4 (24-32 cm)	5 (32-40 cm)	6 (40-48 cm)	A	AB	B
12	1	1	112.50	141.67	212.50	279.17	341.67	400.00	0.88	2.54	1.92
		2	120.83	162.50	245.83	337.50	400.00	400.00	0.75	2.29	2.79
	2	1	125.00	187.50	270.83	320.83	370.83	395.83	0.71	3.00	2.67
		2	112.50	150.00	216.67	350.00	400.00	400.00	0.54	2.17	2.33
	3	1	125.00	191.67	250.00	329.17	375.00	400.00	0.75	2.71	2.25
		2	129.17	195.83	237.50	283.33	375.00	400.00	0.79	2.08	2.04
	4	1	116.67	141.67	216.67	283.33	333.33	383.33	0.75	1.83	2.25
		2	120.83	162.50	170.83	216.67	283.33	370.83	0.71	1.88	2.08
13	1	1	137.50	191.67	266.67	354.17	391.67	400.00	0.96	2.54	2.33
		2	120.83	179.17	258.33	320.83	366.67	400.00	1.38	2.58	2.33
	2	1	112.50	183.33	266.67	341.67	395.83	400.00	1.17	2.25	2.96
		2	129.17	195.83	266.67	345.83	395.83	400.00	1.21	3.29	2.83
	3	1	116.67	187.50	291.67	383.33	400.00	400.00	0.96	3.29	3.00
		2	100.00	133.33	229.17	312.50	400.00	400.00	1.13	1.92	1.50
	4	1	112.50	166.67	225.00	312.50	395.83	400.00	1.33	2.29	2.04
		2	116.67	187.50	237.50	279.17	362.50	400.00	1.17	2.33	2.17
14	1	1			225.00	300.00	358.33	383.33		2.17	2.25
		2			187.50	254.17	316.67	375.00		2.21	1.96
	2	1			212.50	295.83	358.33	400.00		2.00	2.17
		2			220.83	320.83	391.67	400.00		2.13	2.08
	3	1			216.67	300.00	387.50	395.83		2.33	2.33
		2			195.83	308.33	400.00	400.00		2.46	2.00
	4	1			212.50	287.50	370.83	400.00		1.96	2.00
		2			208.33	287.50	354.17	383.33		2.46	2.29

* Treatments are 1= Strohm aerator®, 2= B.C. Sub-mulcher®, 3= Control, and 4= Paratill®. Missing values = no available data.

Table 25. 1990 Bulk Densities.

SITE NO.	TRT*	BULK DENSITIES (g/cm³)					
		Ax	Ay	ABx	ABy	Bx	By
1	3			1.52	1.65	1.70	1.65
	4						
2	1						
	2						
	3	1.02	1.00	1.42	1.32	1.40	1.42
	4						
3	1						
	2						
	3	1.31	1.43	1.59	1.56	1.54	1.66
4	1	1.41	1.39	1.45	1.46	1.53	1.55
	2	1.44	1.39	1.44	1.44	1.48	1.46
	3	1.37	1.40	1.46	1.57	1.46	1.51
	4	1.41	1.42	1.44	1.46	1.56	1.51
5	1	1.26	1.41	1.48	1.49	1.55	1.62
	2	1.41	1.39	1.52	1.58	1.53	1.62
	3	1.39	1.42	1.54	1.56	1.55	1.51

* Treatments are 1= Strohm aerator®, 2= B.C. Sub-mulcher®, 3= Control, and 4=Paratill®.
Missing values = no available data.

Table 25. 1990 Bulk Densities (Continued).

SITE NO.	TRT*	BULK DENSITIES (g/cm³)					
		Ax	Ay	ABx	ABy	Bx	By
6	1						
	2						
	3	1.41	1.45	1.53	1.53	1.60	1.55
7	1			1.42	1.51	1.54	1.49
	2			1.52	1.50	1.47	1.49
	3			1.41	1.40	1.41	1.37
	4			1.51	1.45	1.54	1.31
8	1						
	2						
	3	1.49	1.45	1.61	1.55	1.49	1.54
9	1						
	2						
	3			1.49	1.50	1.53	1.58
10	1						
	2						
	3	1.52	1.41	1.56	1.56	1.58	1.58

* Treatments are 1= Strohm aerator®, 2= B.C. Sub-mulcher®, 3= Control, and 4= Paratill®.
Missing values = no available data.

Table 25. 1990 Bulk Densities (Concluded).

SITE NO.	TRT*	BULK DENSITIES (g/cm³)					
		Ax	Ay	ABx	ABy	Bx	By
11	1						
	2						
	3	1.51	1.33	1.58	1.51	1.48	1.60
	4						
12	1	1.53	1.48	1.58	1.59	1.68	1.63
	2	1.38	1.35	1.41	1.46	1.59	1.50
	3	1.54	1.49	1.66	1.57	1.63	1.59
	4	1.50	1.52	1.64	1.59	1.68	1.59
13	1	1.39	1.50	1.54	1.54	1.64	1.58
	2	1.52	1.52	1.57	1.67	1.77	1.86
	3	1.49	1.39	1.50	1.49	1.57	1.57
	4	1.52	1.61	1.64	1.61	1.63	1.61
14	1			1.42	1.39	1.56	1.54
	2			1.37	1.34	1.49	1.39
	3			1.35	1.37	1.48	1.40
	4			1.34	1.44	1.43	1.46

* Treatments are 1= Strohm aerator®, 2= B.C. Sub-mulcher®, 3= Control, and 4= Paratill®.
Missing values = no available data.

Table 26. 1990 Worm, Pore, Compaction and Subsoiler Ratings.

SITE NO.	TRT*	REP	WORMS			PORES			CR	SR
			A**	AB	B	A	AB	B		
1	3	1	3	2	2	8	6	7	3	1
		2	2	2	2	7	6	7	3	1
	4	1	3	3	3	8	7	7	2	1
		2	3	2	3	8	6	8	3	1
2	1	1	3	2	2	8	5	6	5	1
		2	3	2	2	8	7	7	3	1
	2	1	3	2	3	8	6	8	4	1
		2	3	2	3	8	7	7	2	1
	3	1	3	2	2	8	7	7	3	1
		2	3	3	3	8	7	8	2	1
	4	1	3	3	2	8	7	7	2	1
		2	3	2	2	8	5	7	4	1
3	1	1	3	2	2	8	4	7	4	1
		2	2	2	2	7	4	7	4	1
	2	1	2	2	3	8	4	7	4	1
		2	3	1	1	8	6	5	5	1
	3	1	3	1	2	8	4	7	5	1
		2	3	1	2	8	4	7	5	1
4	1	1	3	2	3	8	6	8	2	1
		2	3	2	3	8	7	8	2	1
	2	1	3	2	3	8	6	8	2	1
		2	3	2	3	8	6	8	2	1
	3	1	3	2	3	8	6	8	2	1
		2	2	2	3	7	6	8	2	1
	4	1	3	3	3	8	7	8	1	2
		2	3	3	3	8	8	8	1	2
5	1	1	2	2	2	8	6	7	2	1
		2	2	2	2	8	6	7	2	1
	2	1	2	1	2	7	6	7	3	1
		2	2	1	2	8	6	7	3	1
	3	1	2	1	2	8	6	7	3	1
		2	2	2	2	8	6	7	2	1

* Treatments are 1= Strohm aerator®, 2= B.C. Sub-mulcher®, 3= Control, and 4= Paratill®.
** A, AB and B represent soil layers.
CR = compaction rating, SR = subsoiling rating.
Missing values = no available data.

Table 26. 1990 Worm, Pore, Compaction and Subsoiler Ratings (Continued).

SITE NO.	TRT*	REP	WORMS			PORES			CR	SR
			A**	AB	B	A	AB	B		
6	1	1	2	1	1	8	5	6	4	1
		2	2	1	2	8	4	7	4	1
	2	1	2	1	1	8	6	7	4	1
		2	2	1	1	8	4	6	4	1
	3	1	2	1	1	8	5	6	4	1
		2	3	2	2	8	6	7	3	1
7	1	1	3	2	2	8	6	7	3	2
		2	3	1	2	8	6	7	3	1
	2	1	3	2	2	8	6	7	3	1
		2	3	1	1	8	5	6	4	1
	3	1	3	1	2	8	6	7	3	1
		2	3	1	2	8	5	6	4	1
	4	1	2	2	2	8	6	7	3	1
		2	2	2	1	8	5	7	3	2
8	1	1	3	2	2	8	7	7	2	1
		2	2	2	2	8	7	7	2	1
	2	1	2	1	2	8	6	7	2	1
		2	3	2	2	8	7	7	2	1
	3	1	3	2	2	8	6	7	2	1
		2	3	2	3	8	6	7	3	1
9	1	1	2	1	2	8	5	6	4	1
		2	2	1	2	7	5	7	4	1
	2	1	3	1	1	8	6	6	4	1
		2	2	1	1	7	5	6	5	1
	3	1	2	1	1	7	5	7	4	1
		2	2	1	1	8	6	7	4	1
10	1	1	2	1	2	8	6	7	3	1
		2	2	1	1	8	6	7	4	1
	2	1	2	1	1	8	6	6	3	1
		2	2	1	1	8	5	6	4	1
	3	1	3	1	2	8	5	6	4	1
		2	2	1	1	8	5	6	4	1

* Treatments are 1= Strohm aerator®, 2= B.C. Sub-mulcher®, 3= Control, and 4= Paratill®.
** A, AB and B represent soil layers.
CR = compaction rating, SR = subsoiling rating.
Missing values = no available data.

Table 26. 1990 Worm, Pore, Compaction and Subsoiler Ratings (Concluded).

SITE NO.	TRT*	REP	WORMS			PORES			CR	SR
			A**	AB	B	A	AB	B		
11	1	1	2	2	2	8	6	7	3	1
		2	2	2	3	8	6	8	2	1
	2	1	3	2	2	8	6	7	3	1
		2	2	2	2	8	6	7	2	1
	3	1	2	1	2	8	6	7	3	1
		2	2	2	3	8	6	8	2	1
	4	1	2	1	2	8	5	7	3	1
		2	3	1	2	8	5	7	4	1
12	1	1	3	2	2	8	6	7	2	1
		2	3	2	2	8	7	7	2	1
	2	1	3	1	2	8	6	7	3	1
		2	3	1	2	8	6	7	3	2
	3	1	3	1	2	8	6	7	3	1
		2	2	1	2	7	6	7	3	1
	4	1	3	2	2	8	7	7	2	2
		2	2	1	2	8	6	7	2	1
13	1	1	3	1	2	8	5	7	4	1
		2	3	1	2	8	6	7	3	1
	2	1	3	1	2	8	5	7	4	1
		2	3	1	2	8	6	7	3	1
	3	1	3	1	2	8	5	7	4	1
		2	3	1	2	8	6	6	3	1
	4	1	2	3	2	8	7	7	2	1
		2	3	2	2	8	6	7	3	1
14	1	1	2	1	2	8	6	7	3	1
		2	2	1	2	8	5	7	4	1
	2	1	2	1	2	8	5	7	4	1
		2	2	1	3	8	5	7	4	1
	3	1	2	1	2	8	5	7	4	1
		2	2	1	2	8	4	6	5	1
	4	1	2	2	2	8	6	7	3	1
		2	2	1	2	8	5	7	4	1

* Treatments are 1= Strohm aerator®, 2= B.C. Sub-mulcher®, 3= Control, and 4= Paratill®.
** A, AB and B represent soil layers.
CR = compaction rating, SR = subsoiling rating.
Missing values = no available data.

Table 27. 1990 Soil Fertility Results.

SITE NO.	OM%		FERTILITY (ppm)												pH		
			P			K			Mg			Ca					
	A	AB	A	AB	B	A	AB	B	A	AB	B	A	AB	B	A	AB	B
1	3.7	3.4	33	17		224	195		496	612		2096	2398		6.7	6.6	
2	18.1	5.5	55	11		177	44		481	286		3285	3252		7.3	7.7	
3	5.6	5.0	51	23		257	106		237	294		4259	4135		7.7	7.7	
4	5.5	4.9	27	6		242	176		305	266		2753	3010		6.7	6.8	
5	4.7	4.3	25	11		219	197		364	429		2561	2733		7.5	6.4	
6	4.3	4.2	21	16		268	221		482	482		2993	2893		6.3	6.5	
7	4.2	3.7	42	22		210	280		516	580		2804	3632		6.5	7.0	
8	4.9	4.2	65	23		305	199		607	579		3003	3101		6.9	6.8	
9	4.3	4.1	55	45		317	258		573	576		3254	3287		6.4	6.6	
10	4.5	3.8	62	51		263	243		412	382		3544	3478		7.3	7.5	
11	4.1	3.6	24	15		139	120		399	441		2837	3346		7.2	7.5	
12	3.9	2.9	26	10		153	147		285	542		1414	1794		5.9	6.7	
13	4.0	4.3	15	10		186	176		313	342		2109	2277		6.0	6.4	
14	6.8	6.7	42	41		239	208		541	529		3320	3239		6.2	6.0	

Missing values = no available data.

Table 28. 1990 Past Yield and Management Factors.

SITE NO.	YR CORN	YR SOY	FACA	TT COV.	PASS	CUM Wt./Ft.	T1 HP	T2 HP	T3 HP
1	113	22	3	181	7	6880	140	85	
2									
3									
4		34	2	95	3	2667	110	50	
5	130	43	2	147	4	2884	160	120	66
6	129	45	2	135	4	3640	130	60	
7	190	38	2	212	7	5530	135	85	40
8	164	50	2	76	3	2800	140	130	120
9	27	44	2	194	5	5040	145	45	
10	153	54	2	234	8	7190	160	95	80
11	154	52	2	237	8	7130	160	95	80
12	147	47	2	209	5	4370	125	120	
13	110	44	2	138	4	3420	185	150	100
14	152	52	2	167	4	4190	170	120	70

Note: See Appendix C for explanation of parameter codes.
Missing values = no available data.

Table 29. 1990 Management Factors: Fertilizer Additions (kg/ha).

SITE	N ADD	P ADD	K ADD
1	0	0	0
2			
3			
4	0	0	0
5	104	31	31
6	0	0	0
7	103	90	134
8	162	67	67
9	0	168	140
10	233	146	112
11	233	146	112
12	210	90	45
13	0	0	0
14	206	83	34

Note: See Appendix C for explanation of parameter codes.
Missing values = no available data.

7.3 APPENDIX C

Variables used in Pearson Correlation Analyses - Codes and Explanations.

DJ1 to 6 Dickey-john® penetrometer reading (lbs/in²) (maximum).

DJ1	0 - 8 cm
DJ2	8 - 16 cm
DJ3	16 - 24 cm
DJ4	24 - 32 cm
DJ5	32 - 40 cm
DJ6	40 - 48 cm

PO Pocket penetrometer reading (kg/cm²) (maximum).

POA	in A horizon (approx. 0 - 12 cm)
POAB	in AB horizon (approx. 12 - 25 cm)
POB	in B horizon (approx. 25 - 35 cm)

BD Bulk density, dry weight basis (g/cm³).

BDA	two replicates in A horizon
BDAB	two replicates in AB horizon
BDB	two replicates in B horizon

W Earthworm abundance based on a field estimate of earthworm numbers in a 25 x 25 cm square 10 cm thick, in the A, AB, or B layers.

1 = none to few	3 = moderate (5 - 10)
2 = few (< 5)	4 = many (> 10)

P Pores in each layer A, AB, and B in accordance with the classes of McKeague et al. (1986) simple system ranked as follows to reflect increasing pore volume.

1 = IA	5 = VIA
2 = IVA or IVB	6 = VIB
3 = VA	7 = VIIA
4 = VB	8 = VIIB

CR Compaction rating, a subjective numerical rating based on appearance and consistence of the AB layer in relation to the B layer and to undisturbed (fence-row) soils.

1 = none	4 = moderate
2 = slight	5 = moderate-severe
3 = slight-moderate	6 = severe

SR	Subsoiling effectiveness rating, a subjective numerical rating based on apparent loosening of the compacted layer in relation to the control. SR1 = first year subsoiler rating, % of soil that is shattered in a metre width 1 = 0-10% 2 = 11-20% 3 = 21-30% 4 = 31-40% SR2 = second year subsoiler rating, residual effect of the subsoiler shank (visual) 1 = no 2 = yes
Y5Corn	Farmer's reported average corn yields in bu/acre, 1985-1989 or 1986-1990 on the test field.
Y5Soy	Farmer's reported average soybean yields in bu/acre, 1985-1989 or 1986-1990 on the test field.
FACA	Farmer's compaction assessment of his land. 1 = slight 2 = moderate 3 = severe
TT Cov.	Tractor Tire coverage per year calculated on a percentage basis considering rear tire width, number of rear tires, number of operations, and width of implement. No correction is made for repeat tracking. For example, total rear tire width in feet x number of passes per 100 feet width x number of operations = total tire coverage per year in %. [6 feet x 100/15 (for a 15 foot implement) x 6 operations = 238% coverage]
Pass	Number of passes or field operations in 1989 or 1990. Subsoiling was included as an operation but harvesting was omitted (1989), and this applies to all farms.
OM	Organic matter content in percent, in the A or AB soil layers.
Sand	Sand content in percent, in the A, AB, or B layers as determined in 1989.
Silt	Silt content in percent, in the A, AB, or B layers as determined in 1989.
Clay	Clay content in percent, in the A, AB, or B layers as determined in 1989.
Nadd	Total amount of fertilizer nitrogen applied in 1989 or 1990 in kg/ha.
Padd	Total amount of fertilizer phosphorous applied in 1989 or 1990 in kg/ha.
Kadd	Total amount of fertilizer potassium applied in 1989 or 1990 in kg/ha.

Pfe	Phosphorous fertility level (ppm) based on soil tests sampled in November 1989 or October 1990 in the A, AB, and B soil layers.
Kfe	Potassium fertility level (ppm) based on soil tests sampled in November 1989 or October 1990 in the A, AB, and B soil layers.
Mgfe	Magnesium fertility level (ppm) based on soil tests sampled in November 1989 or October 1990 in the A, AB, and B soil layers.
Cafe	Calcium fertility level (ppm) based on soil tests sampled in November 1989 or October 1990 in the A layer.
pH	Soil reaction in the A, AB, and B soil layers.
CumWF	Estimated total loading by tractors per 100 foot width of field, (implements excluded) considering tractor total weight, number of passes per 100 foot width of implement and number of operations.
T1HP	Tractor 1 horsepower. The horsepower rating of the farmer's largest tractor.
T2HP	Tractor 2 horsepower. The horsepower rating of the farmer's second largest tractor.
T3HP	Tractor 3 horsepower. The horsepower rating of the farmer's third largest tractor.

7.4 APPENDIX D

Layout of Treatments at Each of the Field Sites (Not to Scale).

Figure No.	Site No.	Farmer	Page No.
20	1	Ken Bee	92
21	2	Brock Bradley	93
22	3	"	94
23	4	Peter Cumming	95
24	5	Robert Farquharson	96
25	6	John Hoy	97
26	7	Murray Johnstone	98
27	8	R. & G. Jack	99
28	9	Doug Parry	100
29	10	Garfield Parry	101
30	11	Mark Parry	102
31	12	Brian Skipper	103
32	13	Elwin Vince	104
33	14	Stanley Wonnacott	105

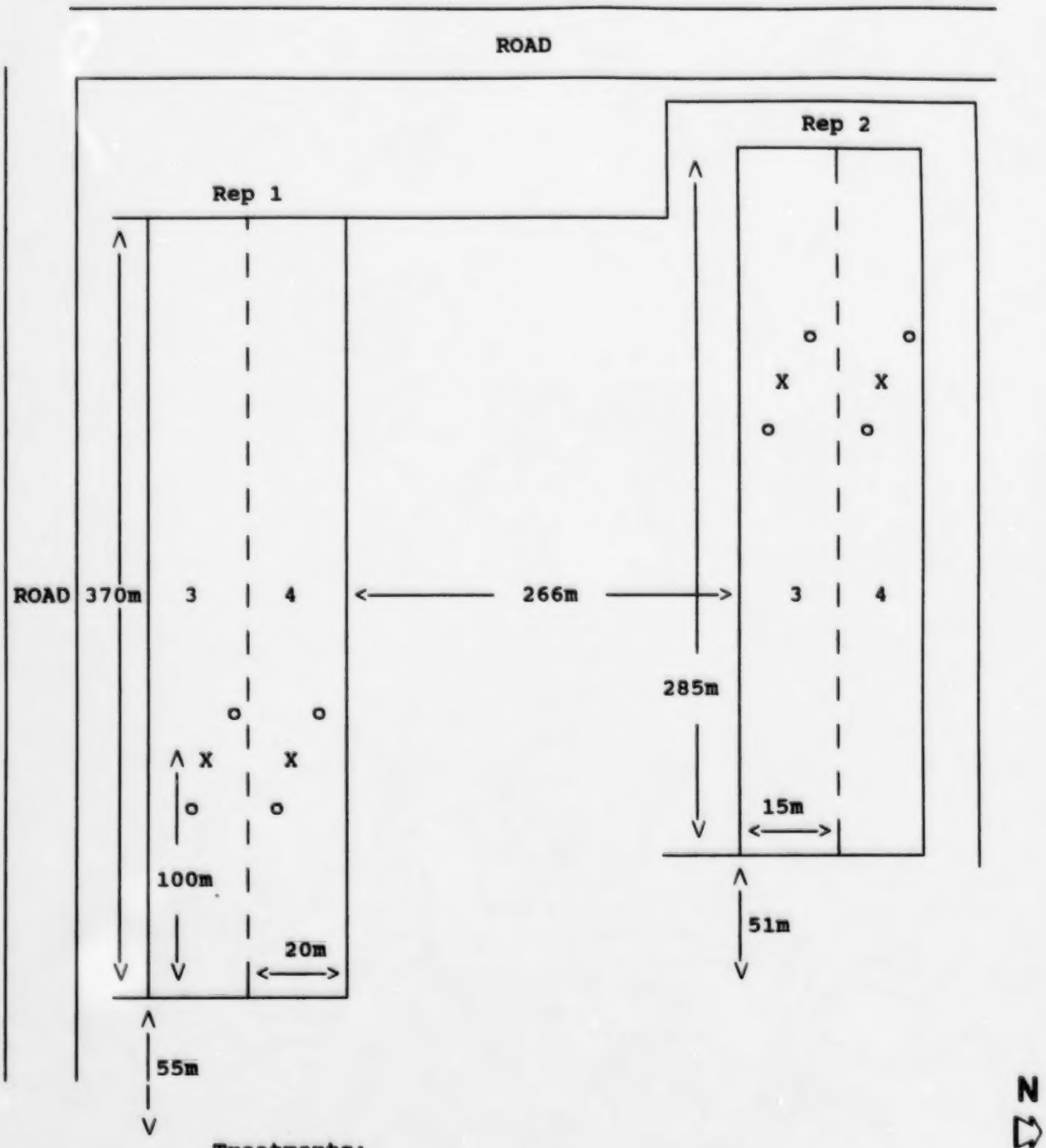
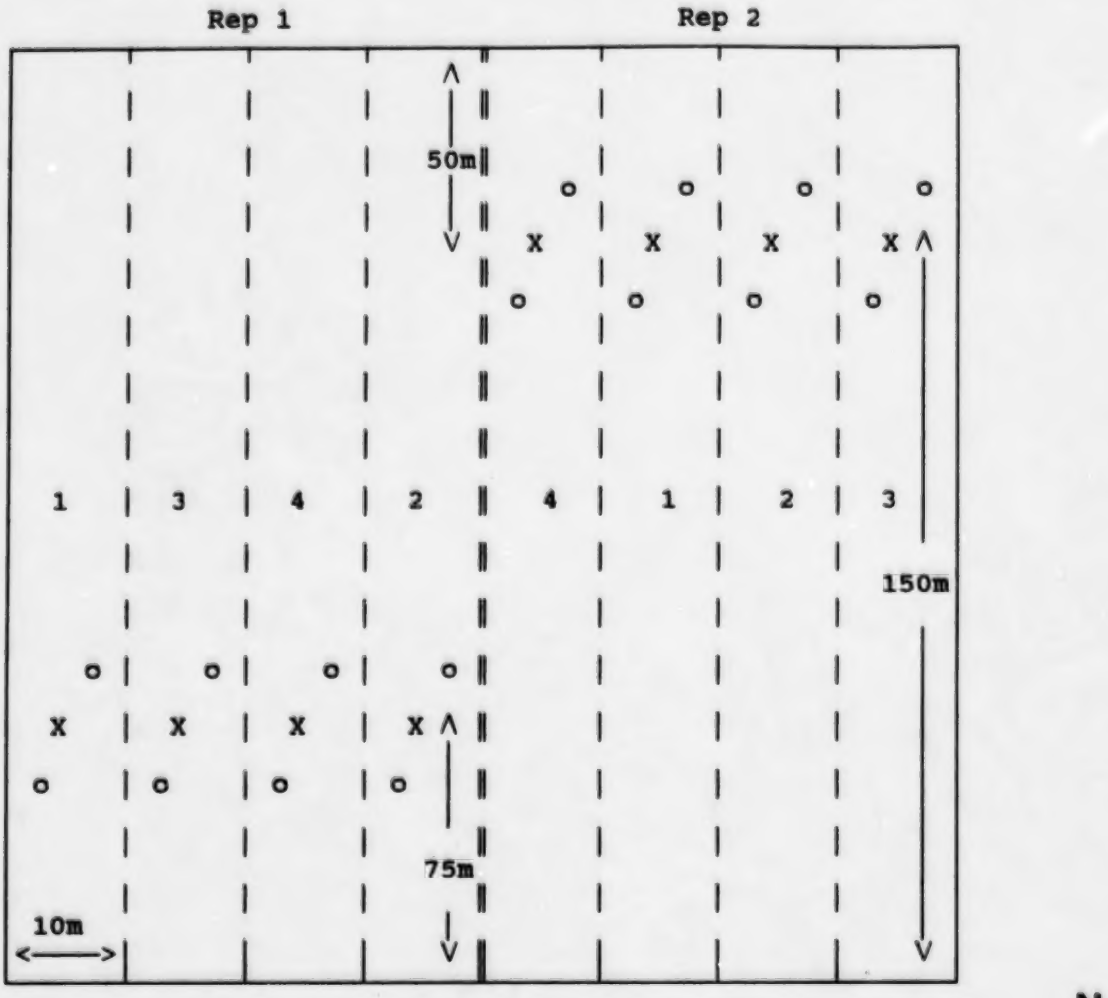


Figure 20. Site 1 (Bee) Layout of Treatments.

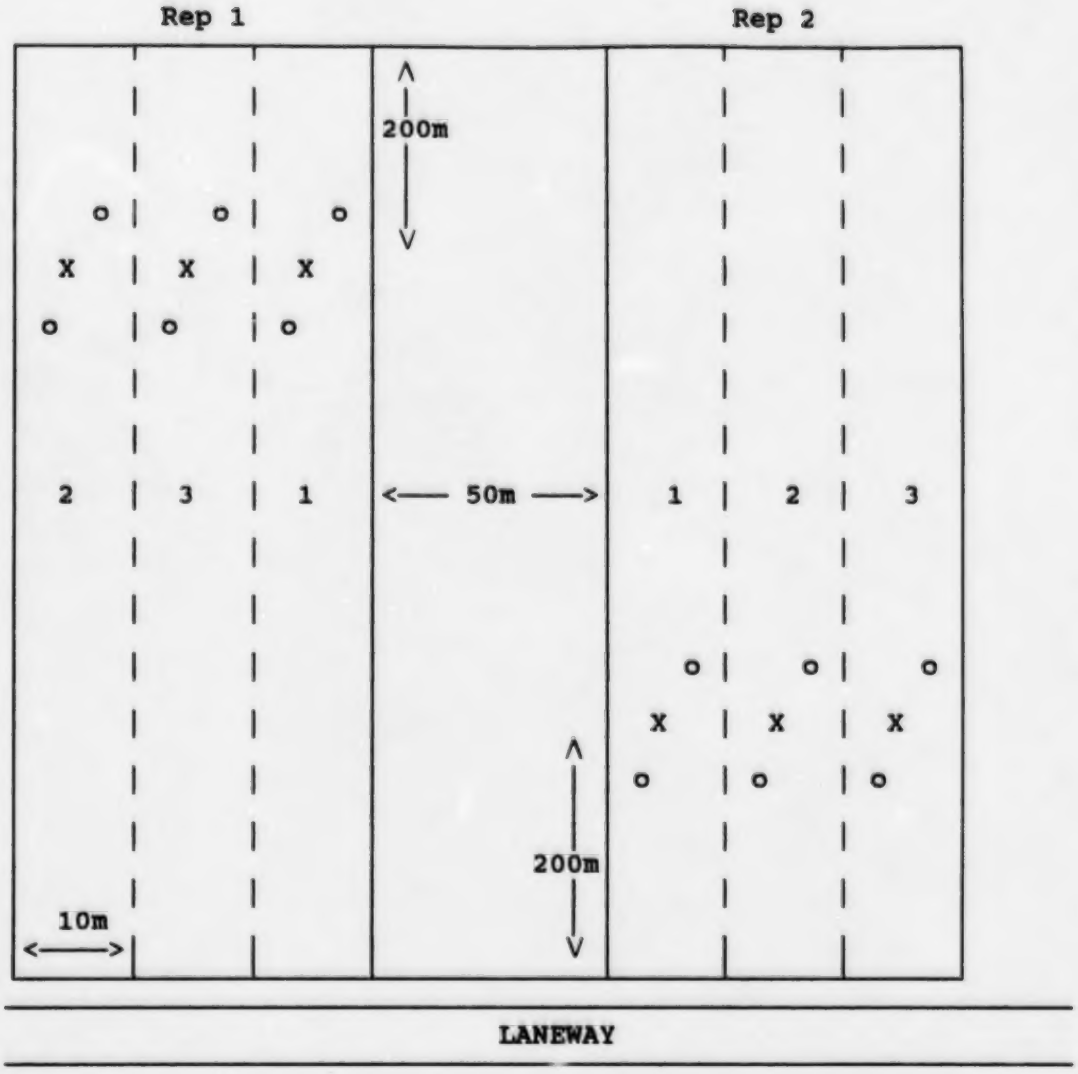


Treatments:

1 = Strohm aerator•
2 = B.C. Sub-Mulcher•
3 = Control
4 = Paratill•

X inspection/sample pit
o inspection pit

Figure 21. Site 2 (Bradley Field #1) Layout of Treatments.

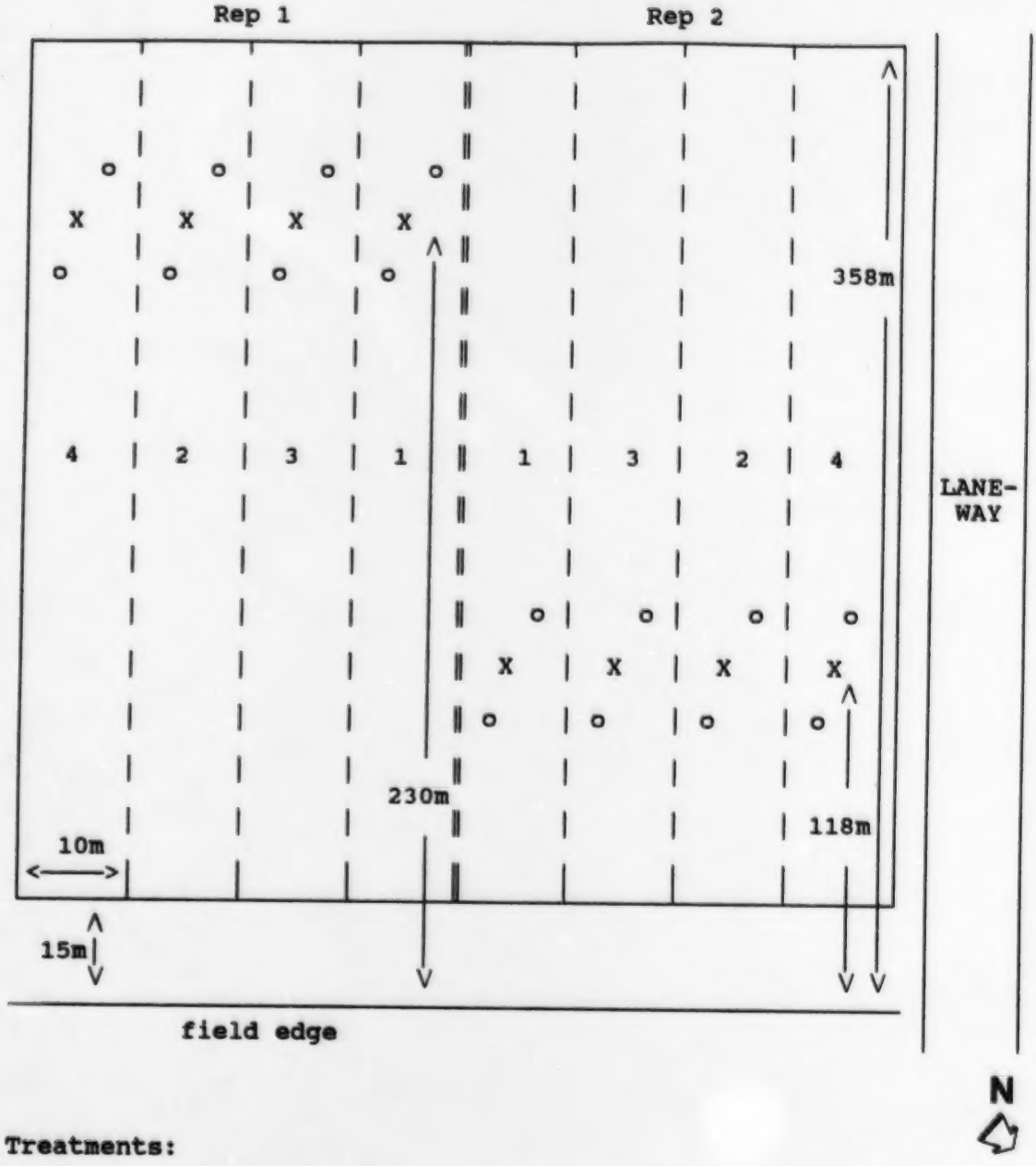


Treatments:

1 = Strohm aerator•
2 = B.C. Sub-Mulcher•
3 = Control

X inspection/sample pit
o inspection pit

Figure 22. Site 3 (Bradley Field #2) Layout of Treatments.

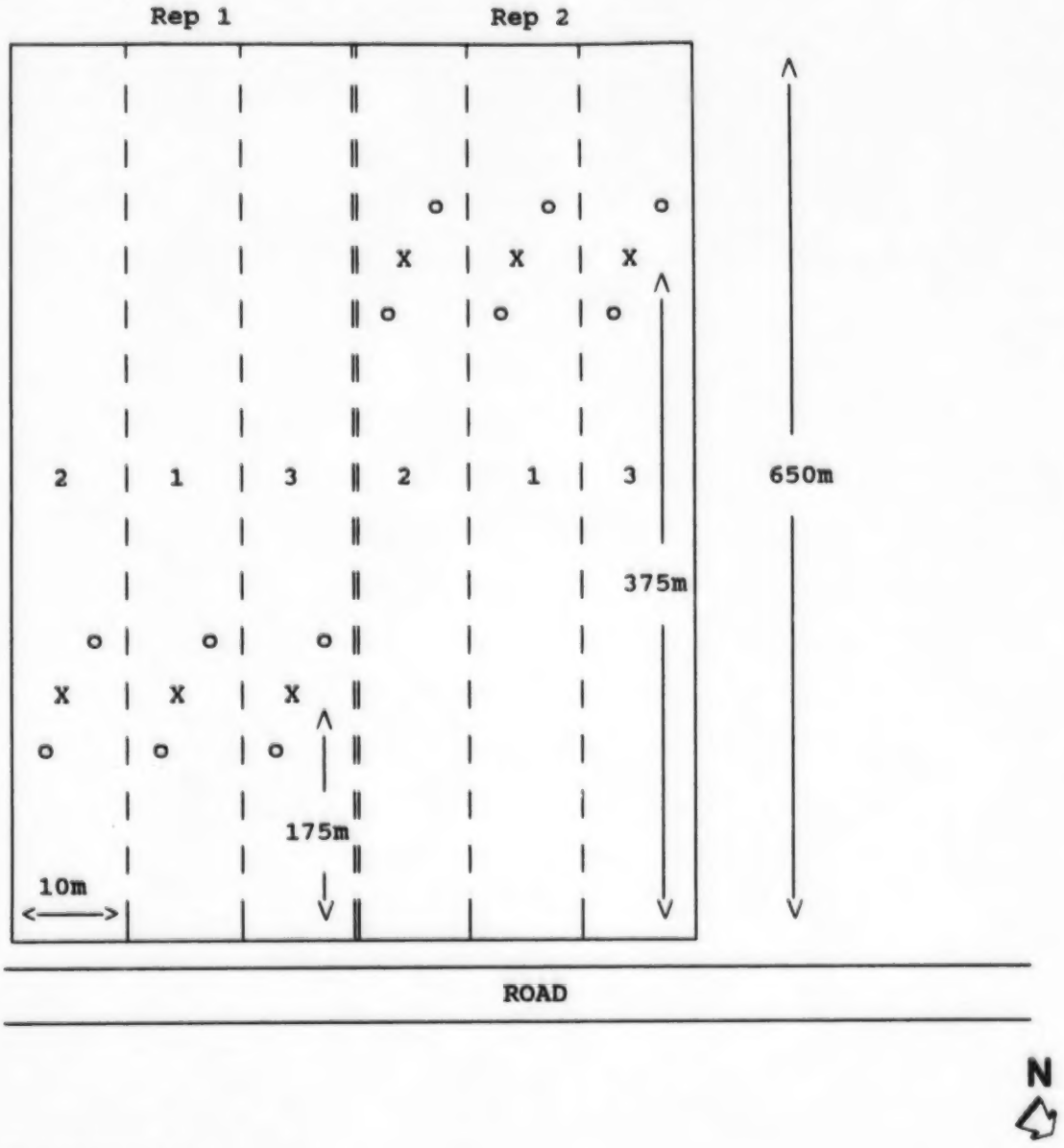


Treatments:

1 = Strohm aerator•
2 = B.C. Sub-Mulcher•
3 = Control
4 = Paratill•

X inspection/sample pit
o inspection pit

Figure 23. Site 4 (Cumming) Layout of Treatments.

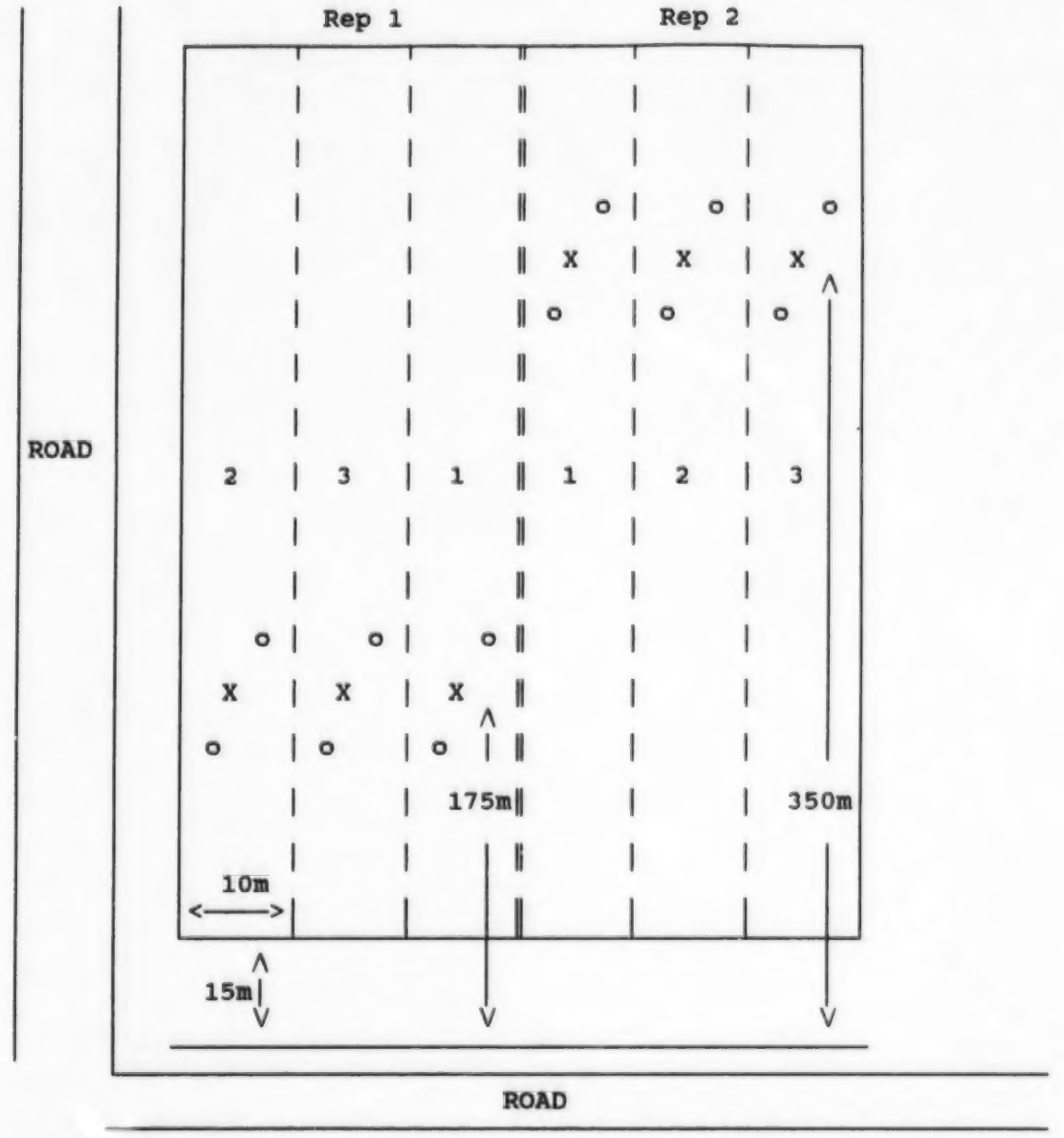


Treatments:

1 = Strohm aerator•
2 = B.C. Sub-Mulcher•
3 = Control

X inspection/sample pit
o inspection pit

Figure 24. Site 5 (Farquharson) Layout of Treatments.

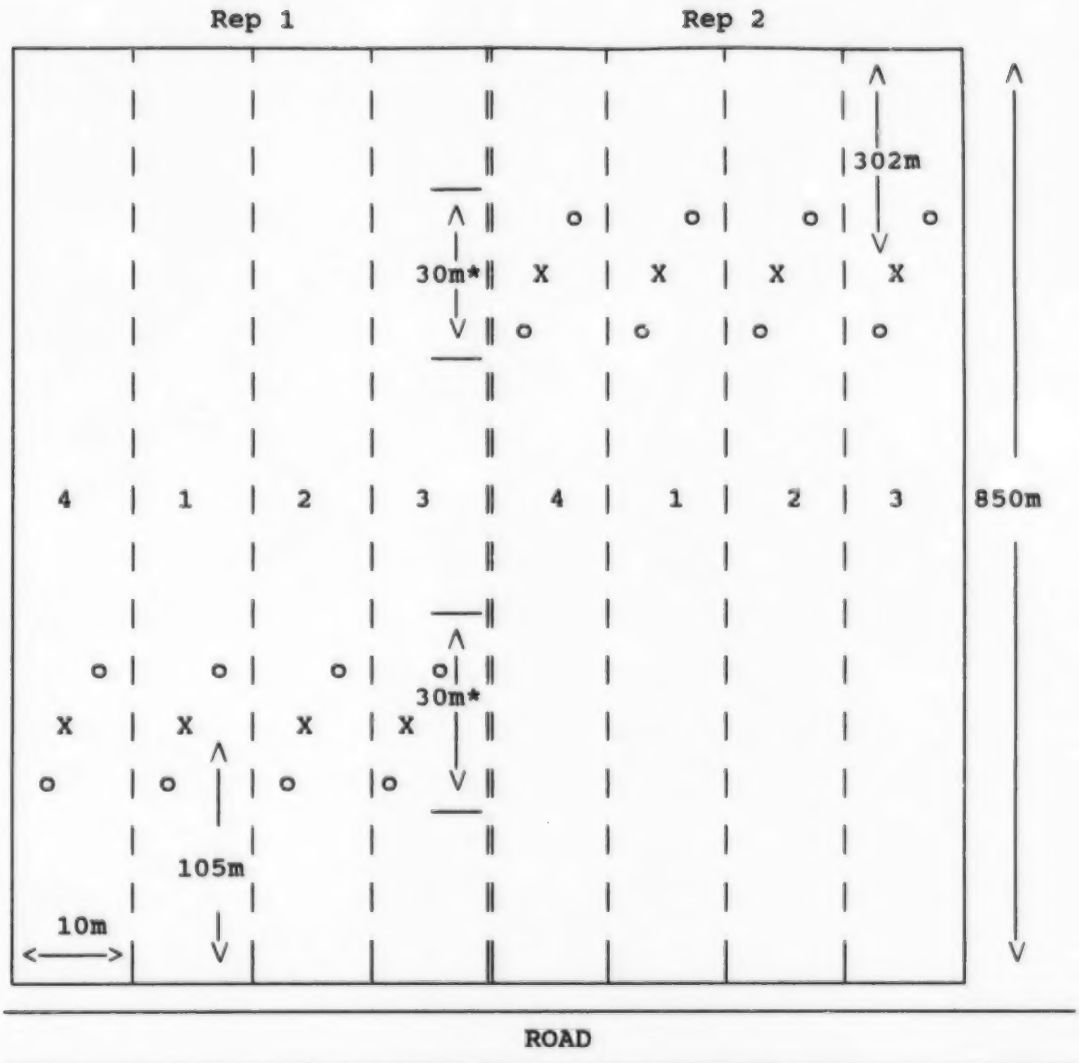


Treatments:

1 = Strohm aerator•
2 = B.C. Sub-Mulcher•
3 = Control

X inspection/sample pit
o inspection pit

Figure 25. Site 6 (Hoy) Layout of Treatments.



*Note: Area in which the Ottawa Tractor logged data.

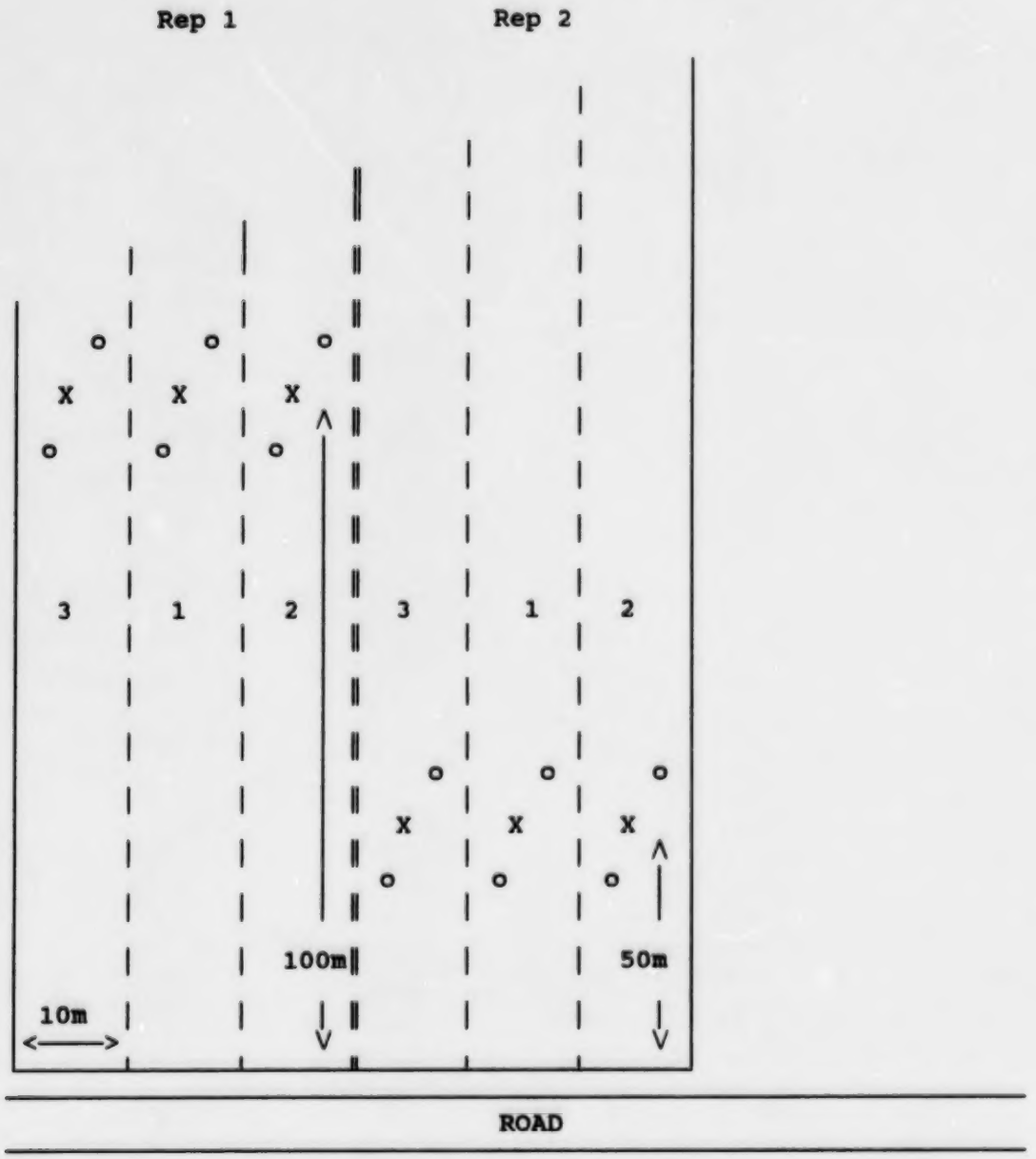
N

Treatments:

1 = Strohm aerator•
2 = B.C. Sub-Mulcher•
3 = Control
4 = Paratill•

X inspection/sample pit
o inspection pit

Figure 26. Site 7 (Johnstone) Layout of Treatments.

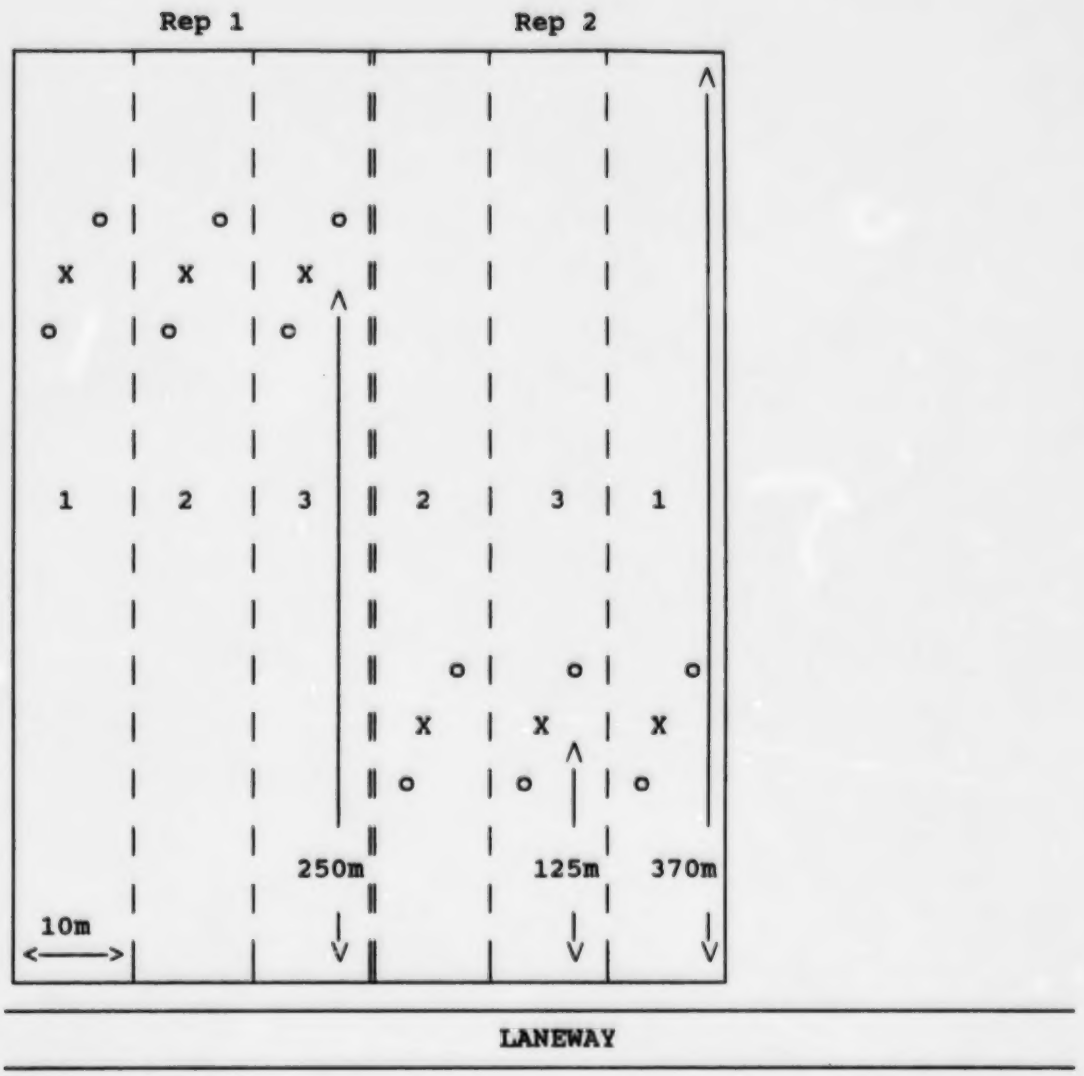


Treatments:

1 = Strohm aerator•
2 = B.C. Sub-Mulcher•
3 = Control

X inspection/sample pit
o inspection pit

Figure 27. Site 8 (Jack) Layout of Treatments.

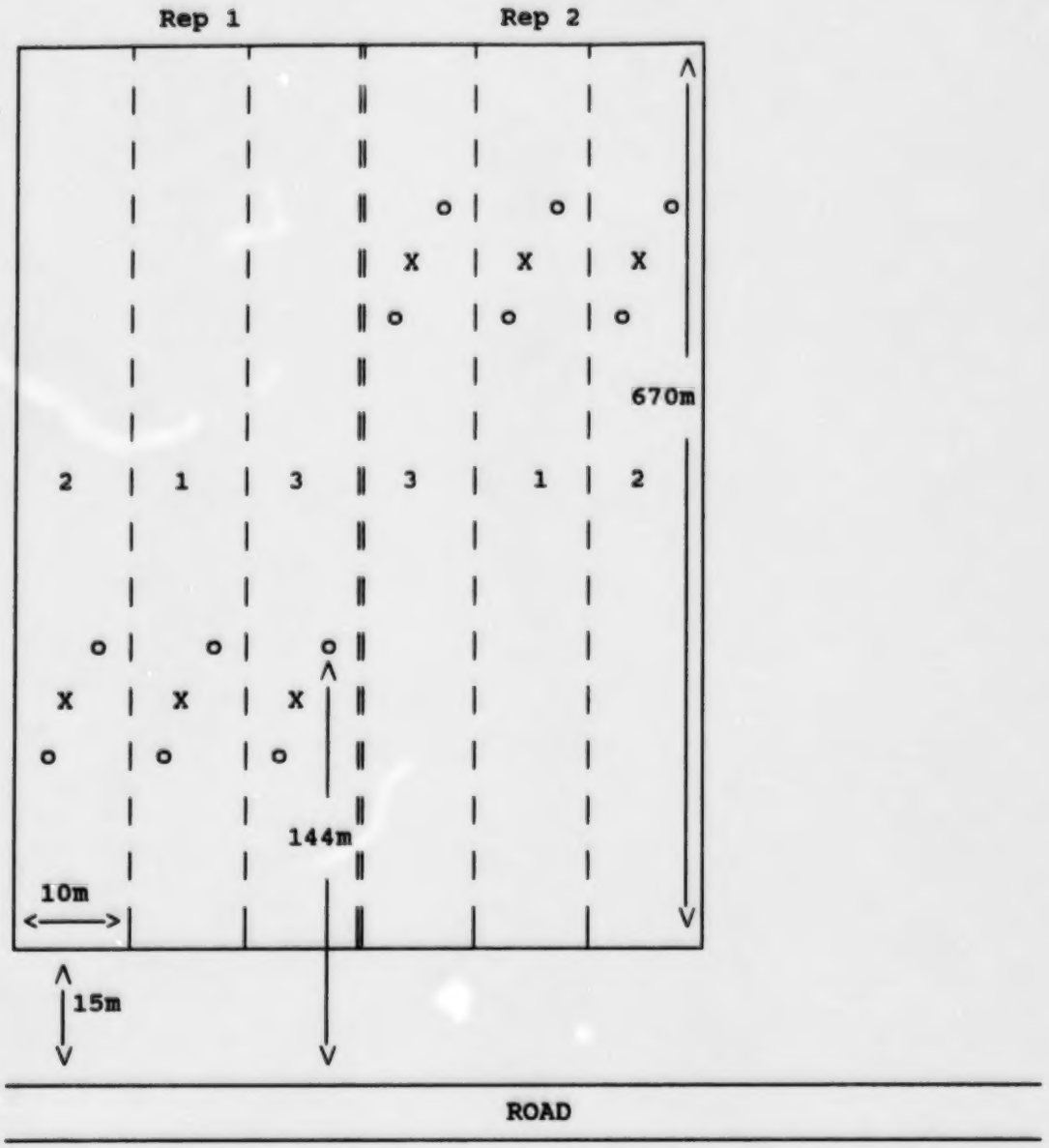


Treatments:

1 = Strohm aerator•
2 = B.C. Sub-Mulcher•
3 = Control

X inspection/sample pit
o inspection pit

Figure 28. Site 9 (D. Parry) Layout of Treatments.

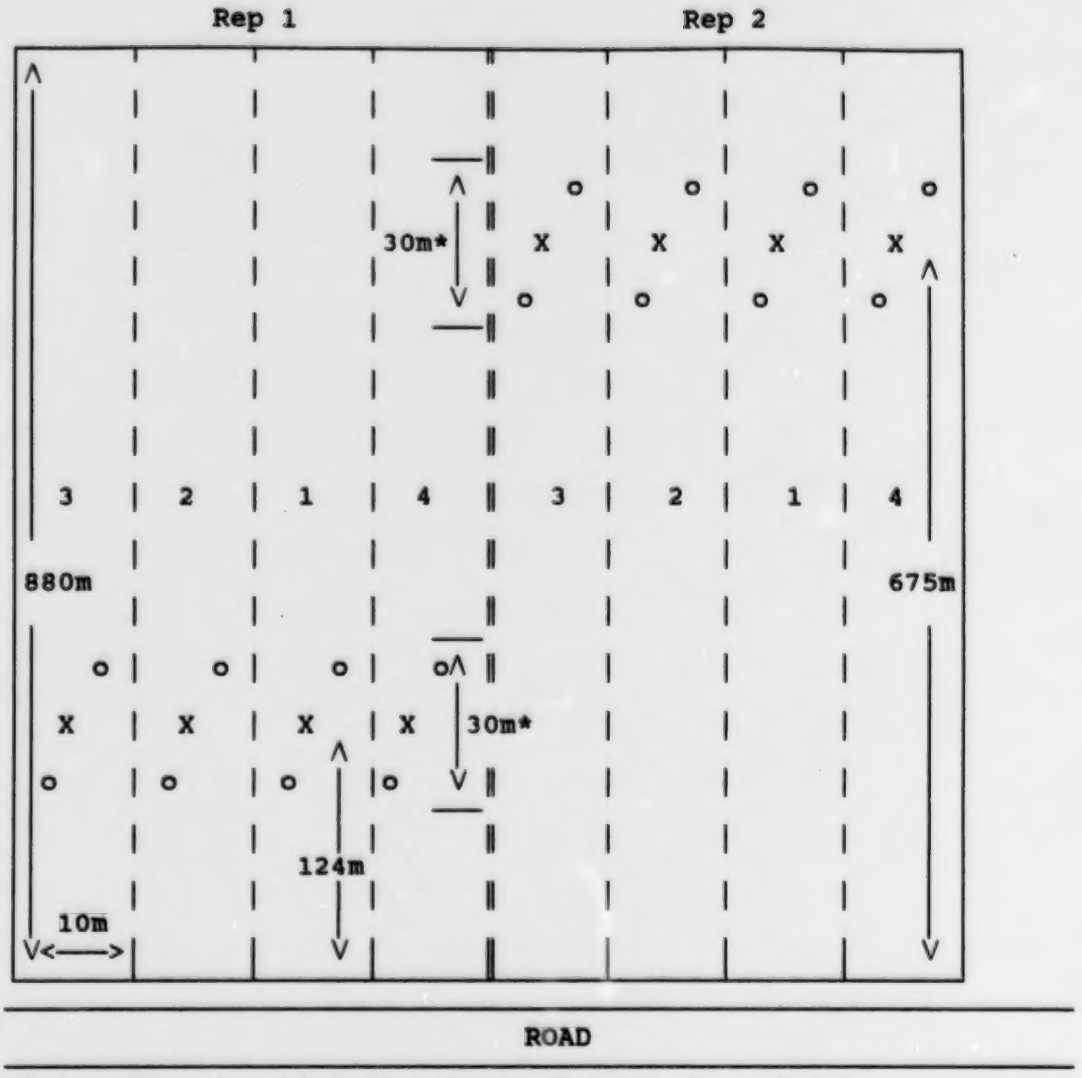


Treatments:

1 = Strohm aerator•
2 = B.C. Sub-Mulcher•
3 = Control

X inspection/sample pit
o inspection pit

Figure 29. Site 10 (G. Parry) Layout of Treatments.



*Note: Area in which the Ottawa Tractor logged data.

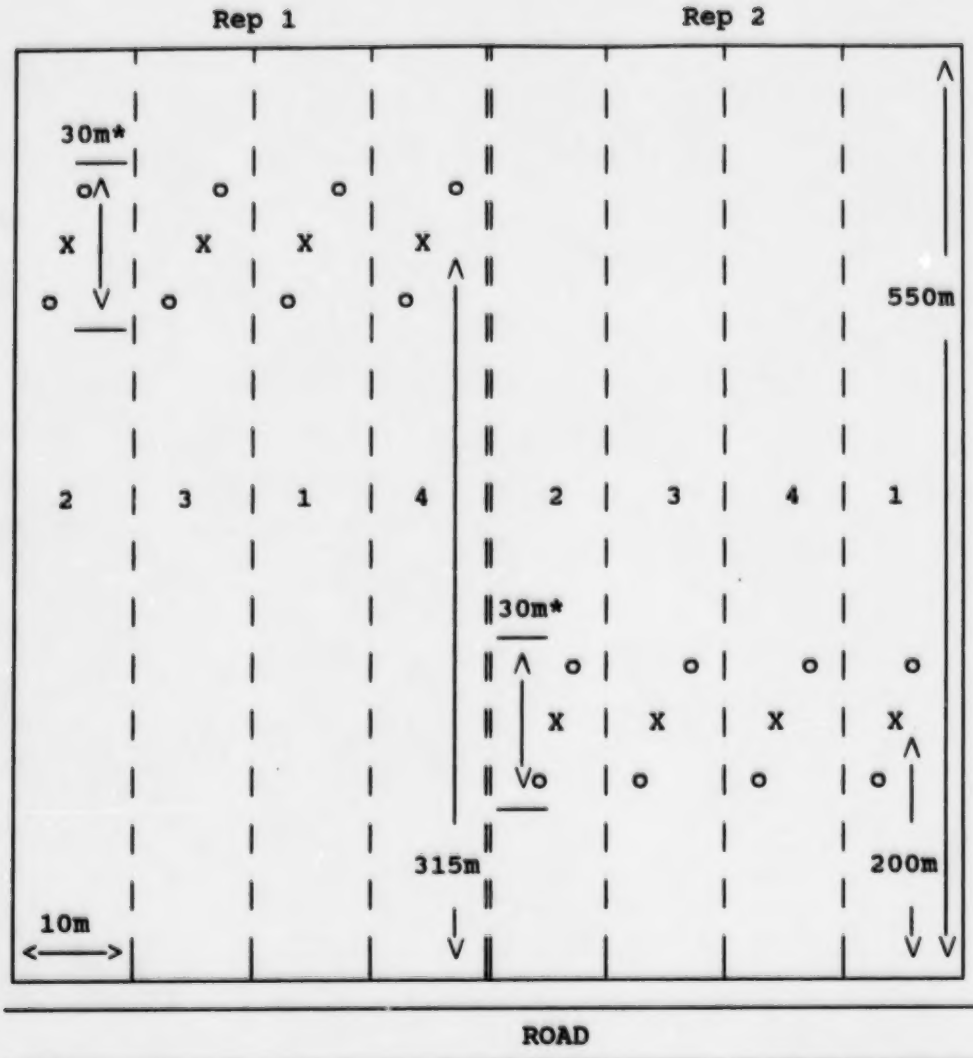
N

Treatments:

1 = Strohm aerator•
2 = B.C. Sub-Mulcher•
3 = Control
4 = Paratill•

X inspection/sample pit
o inspection pit

Figure 30. Site 11 (M. Parry) Layout of Treatments.



*Note: Area in which the Ottawa tractor logged data.

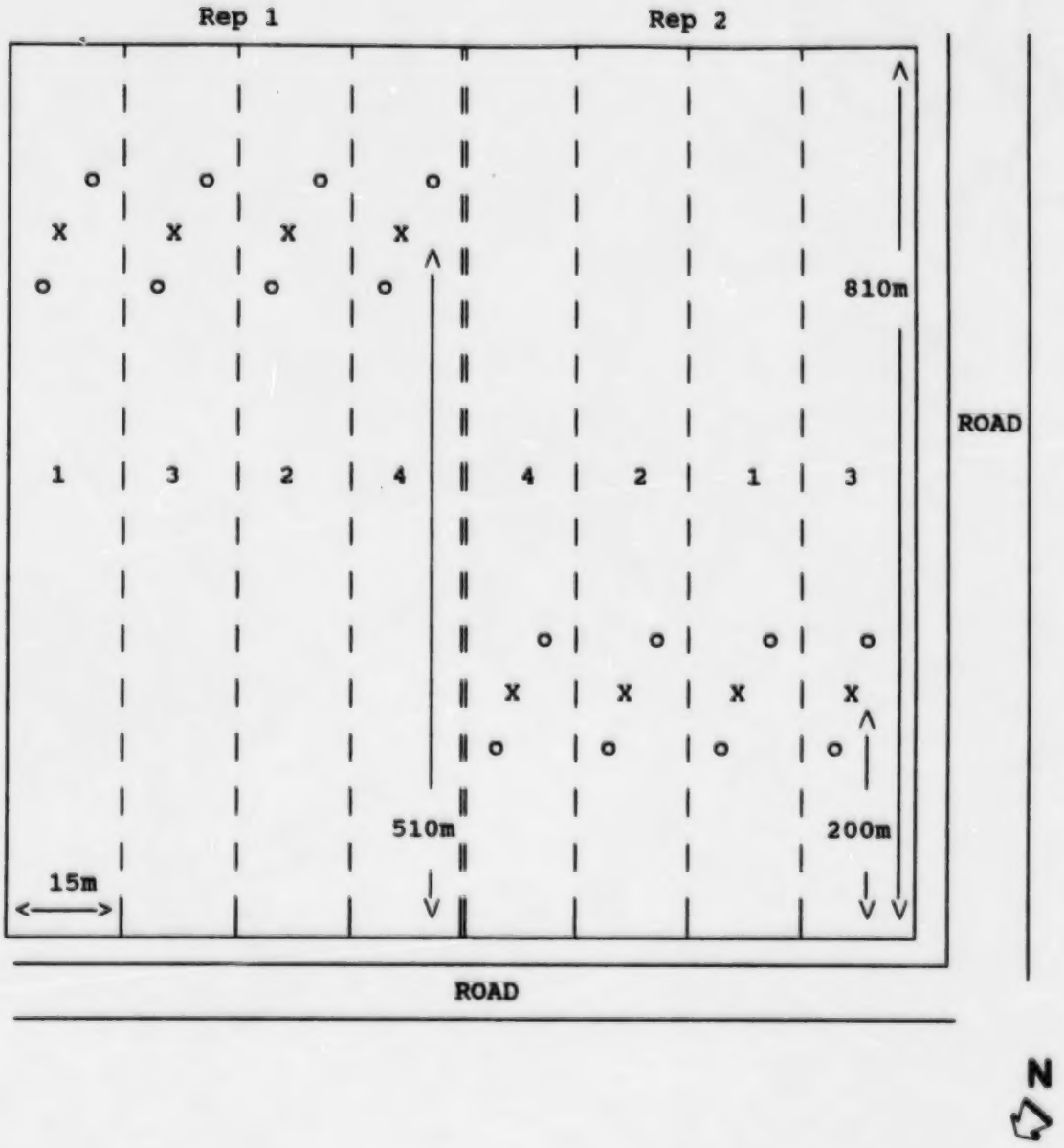
N

Treatments:

1 = Strohm aerator*
2 = B.C. Sub-Mulcher*
3 = Control
4 = Paratill*

X inspection/sample pit
o inspection pit

Figure 31. Site 12 (Skipper) Layout of Treatments.

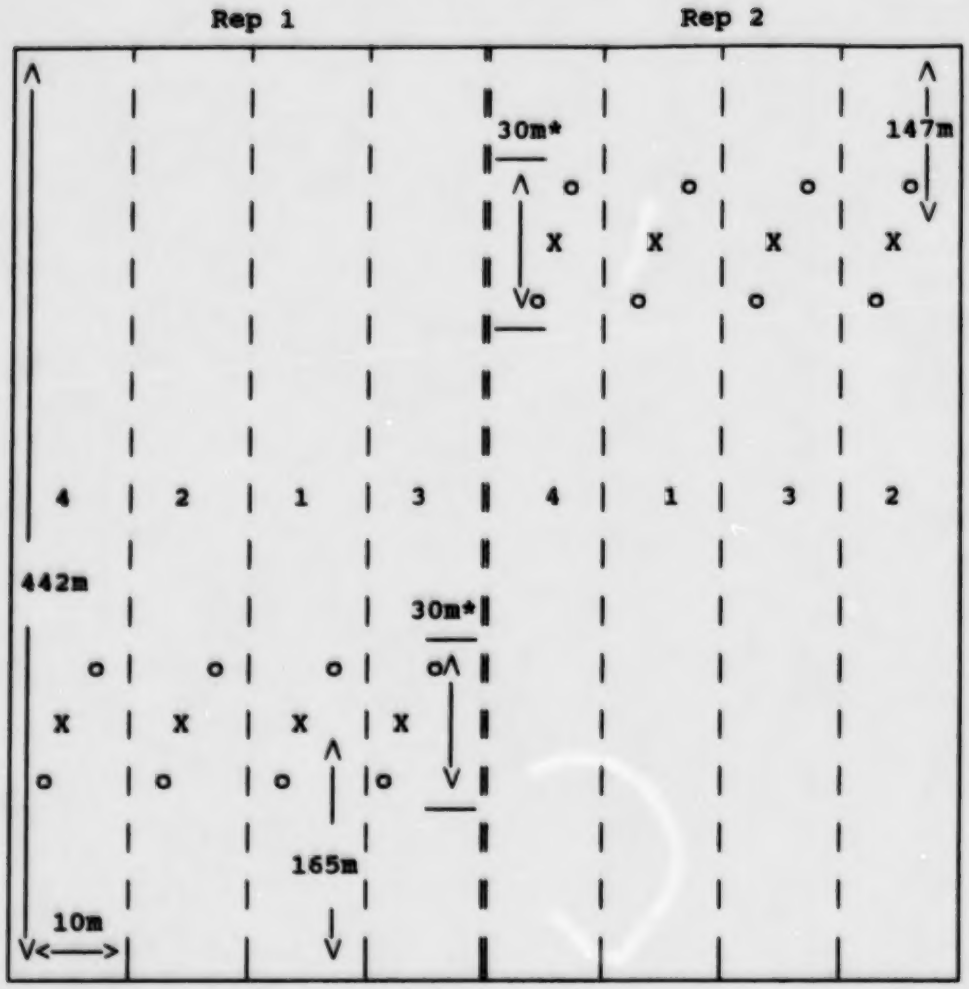


Treatments:

1 = Strohm aerator•
2 = B.C. Sub-Mulcher•
3 = Control
4 = Paratill•

X inspection/sample pit
o inspection pit

Figure 32. Site 13 (Vince) Layout of Treatments.



*Note: Area in which the Ottawa Tractor logged data.

N

Treatments:

1 = Strohm aerator*
2 = B.C. Sub-Mulcher*
3 = Control
4 = Paratill*

X inspection/sample pit
o inspection pit

Figure 33. Site 14 (Wonnacott) Layout of Treatments.